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Role of the geosphere in deep nuclear waste disposal – An England and Wales perspective

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ABSTRACT

To dispose permanently of its higher activity nuclear waste England and Wales have chosen deep geological disposal as the most appropriate solution currently available. The purpose of this paper is to describe the main geological features, events and processes relevant to England and Wales that will need to be considered to demonstrate that a site is suitable for a geological disposal facility (GDF). England and Wales are in the early stages of a GDF siting process in which areas of interest are being evaluated using mainly existing data from surface mapping and hydrocarbon exploration and production. Sites are evaluated consistently under six overarching headings, three of which are impacted by their geological setting – safety, engineering feasibility and value for money. "Suitable" geology is that which is safe during the operational and long-term post-closure period, which could have a GDF and its accessways constructed within it, and which delivers value for money. A GDF needs to fulfil dual safety functions wherever it is located: long-term containment of radionuclides, and isolation of the waste from human actions and from natural processes such as glaciations and earthquakes. The role of the geosphere in delivering these safety functions is to provide a low-flux groundwater environment with geochemical conditions that minimise degradation of the engineered components of the GDF, to promote retention of mobilised radionuclides, and to protect the waste from the impacts of humans and natural processes. The containment function of a GDF is provided by a combination of rock and engineering generally referred to as the multibarrier system. It comprises the engineered barriers – solid wasteforms, canisters, buffers, backfill materials, plugs and seals – that work together with the rock to ensure long-term containment. The GDF Programme in England and Wales seeks to identify suitable geological environments for which bespoke engineered barriers can be tailored to optimize the performance of the multibarrier system. The post-closure period over which independent regulators will require a safety case to demonstrate the long-term containment and isolation capabilities of a GDF is up to 1 million years. The long timescales make post-closure safety assessments a unique feature of deep geological disposal programmes. A comprehensive site characterization programme will use information mostly from seismic surveying and deep investigation boreholes to establish adequate rock availability (host rock depth, thickness, areal extent and compartmentalisation), suitable properties and behaviour of the deep geological environment, and the constructability and operability of a potential GDF site including its surface to subsurface access ways. Nuclear Waste Services, the organisation tasked with developing a GDF in England and Wales, is currently engaged with four Community Partnerships through a volunteer siting process: three in west Cumbria, and one on the English east coast in Theddlethorpe, Lincolnshire. In all of these areas Mesozoic claystones have been provisionally identified as potentially suitable GDF host rocks and are being investigated further, with a dedicated 3D seismic survey acquired off the coast of Cumbria in 2022. The main conclusion to be drawn from this paper is that a GDF could be sited in a large number of geological settings in England and Wales, and that the success of the current siting process will largely depend on engaging effectively with willing communities and building enduring relationships with them.

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1. Purpose and structure

This paper discusses how understanding of geological features, events and processes will be used to select a suitable site for a Geological Disposal Facility (GDF) for the UK's longer lived and higher activity radioactive wastes. Deep geological disposal of radioactive wastes is a global challenge. It aims to remove the enduring cost, environmental and security burden of legacy nuclear wastes and, as an integral part of the whole-lifecycle management of the next generation of nuclear reactors, enables future energy security. The GDF Programme in England and Wales benefits considerably from lessons learned from deep geological disposal programmes in other countries, many of which are further ahead than in the UK. However the focus of this paper is on the geological environment that we have to work with in England and Wales.

The main aim is to examine the properties and processes that need to be understood and taken into account in determining geological suitability: how a GDF will be engineered to match and evolve in concert with the properties of the surrounding geological environment; and how to communicate suitability to communities and other stakeholders.

The paper begins with a review of the primary containment and isolation functions of a GDF wherever it may be located and in whatever geological environment. This is followed by a description of how long-term containment and isolation will be provided by means of the multibarrier system of integrated engineered barriers working together with the natural geo-barrier.

England and Wales policy implementing deep geological disposal is built around community consent (delivered through a test of public support) to proceed with a GDF in an area with suitable geological properties, rather than any notion of selecting the 'best' site (it being widely accepted that a safe GDF could be implemented in many locations and there is no such thing as a 'best' geological site). Throughout the more than one-hundred-year duration of the GDF Programme it will be essential to build long-term trust through partnership with communities and by sharing its findings openly and transparently across a broad cross-section of stakeholders, including the host community. This paper therefore includes a discussion of how the subsurface will be characterized at potential GDF sites, how confidence in geological understanding will grow as data are gathered, how geological and any other subsurface-related uncertainties will be progressively reduced, and of how this process can be communicated effectively.

The core of the paper focuses on a systematic review of the principal geological features, events and processes that are relevant in the UK setting, and for which the design of the multibarrier will need to be optimized. The characteristics of rock type, deformational structure, and groundwater chemistry and movement are the main geological features that impact GDF design to provide long-term containment, whilst continental glaciations and seismicity are the main natural geological events of relevance to the UK that can have effects from which the waste will need to be isolated. A discussion of the impact of excavation-induced rock deformation, or excavation damage, is also included as it needs to be understood throughout GDF design and construction.

2. Context of the deep geological disposal programme

The UK has been accumulating radioactive waste for some 70 years. All the higher activity waste is stored in above-ground structures, mostly at Sellafield in west Cumbria, with the rest at some 25 other sites around the UK. Given the very long time periods over which this waste remains harmful it is axiomatic that it needs to be managed carefully, with the scientifically accepted solution internationally being permanent disposal in a deep geological repository, in England and Wales referred to as a GDF.

GDFs are acknowledged to be an appropriate and safe means of isolating spent fuel and other high-level radioactive waste from the biosphere for very long time periods, with the necessary technologies already available (European Commission, 2011). An underpinning principle of radioactive waste disposal is intergenerational equity: that the generations that benefitted from nuclear technologies should put in place the processes and funding that will lead to disposal of nuclear waste products thus releasing future generations from the burden of security and cost.

In common with almost every other country facing the challenge of how to dispose of its radioactive waste, England and Wales have selected deep geological disposal as their favoured option. Managing radioactive waste disposal in the UK is a devolved responsibility and Scottish policy does not yet consider final disposal, requiring that long-term management of higher activity waste should be in near-surface facilities located as close as possible to the sources of the waste. In England and Wales the process of identifying potential sites for a GDF is consent-based and will require a willing and engaged community and a technically suitable site, with decisions on suitability including considerations of the nature and understanding of the deep geological environment.

England and Wales policy refers throughout to "a" GDF. A single repository is the preferred option for reasons of safety (as low as reasonably practicable) and minimization of the period before which the burden of managing surface storage of waste is retired by its transferral to a permanent disposal facility.

Nuclear Waste Services (NWS) is tasked by the governments of England and Wales with delivering a GDF. As a part of the Nuclear Decommissioning Authority (NDA) NWS is funded through the newly created Department for Energy and Net-Zero. NWS has evolved from a line of predecessor organisations over several decades and has accumulated considerable technical expertise around GDF siting, construction and operation. Whilst required to operate within the constraints of Government policy, NWS is able to exercise considerable freedom in its implementation of technical solutions to the challenges of delivering a GDF. Confidence that a GDF will be safe, timely and represent good value for money will be obtained through independent regulators, mainly the Environment Agencies and the Office for Nuclear Regulation.

The GDF Programme is a designated Nationally Significant Infrastructure Project costing billions of pounds and with the potential to transform communities through long-term investment in jobs, skills and infrastructure. Given the wider political significance of the programme NWS will continue to work closely with its client, the NDA, and sponsor, the Department for Energy and Net-Zero, to balance the technical, strategic, social and political needs of all the key stakeholders.

2.1. The role of communities in the GDF programme

A suitable location for a GDF will be identified through a consent-based process in partnership with communities. Discussions on a proposed location for a GDF can be initiated by anyone or any group of people who wish to propose an area for consideration. Where an initial exchange of information between NWS and interested parties merits further consideration they must jointly inform all relevant principal local authorities and open up discussions more widely in the community. The overriding intention is that the community hosting a GDF plays a key role in approving a proposed site and supporting its construction, operation and decommissioning.

A Working Group will then be formed of the interested parties and the delivery body, guided by an independent chair and a facilitator. Its main purpose is to identify the geographic area within which potentially suitable sites for a GDF can be sought. The Working Group will start to gather information about the people and organisations in the area who are likely to be affected or have an interest in a GDF with a view to identifying members for a formal Community Partnership.

The Community Partnership provides a vehicle for sharing information with the community and to understand how hosting a GDF in their area could fit with the community's vision for its future. Before a decision is made to seek development consent there must be a test of public support to demonstrate that the community is willing to host a

GDF. Relevant principal local authorities in the Community Partnership will have the final say on when to undertake this test. In the event of contested and unresolved technical and/or scientific issues the Third Party Expert Review Mechanism allows NWS and the government to access views provided by appropriately knowledgeable experts selected independently by the learned societies.

NWS is currently engaged with four Community Partnerships – three in Cumbria, northwest England, and one in Theddlethorpe, Lincolnshire, eastern England. All of them have developed through the volunteer process in which initial discussions were instigated by the communities. Detailed evaluation of these sites commenced in 2022 with no decisions based on comparative technical assessments due until 2026.

2.2. Scheduling of the GDF programme

The implementation of a GDF is organised around the following activities, the scheduling of which is complex due to the many interdependencies that connect them, and which collectively contribute to the expected long duration of the programme.

1. Engagement with a willing community. The GDF Programme can only proceed at the rate at which interested communities are able and prepared to progress. In particular a community will need to have confidence that a GDF can be developed and managed safely, that its benefits to the community will be realized, and that the regulatory processes will continue to provide protection throughout GDF operations.
2. Selecting a suitable site. There is no 'off-the-shelf' solution for a GDF because the detailed design and safety case are effectively bespoke, governed by surface and subsurface conditions at specific sites. Throughout the programme the envelope of possible designs will be progressively adapted as information becomes available through iterative cycles of field data acquisition, interpretation and synthesis.
3. Managing a highly regulated major infrastructure project. Planning for each major stage in the GDF Programme needs to make provision for an extensive permitting process. Deep investigation boreholes as well as the GDF itself require approval by the Secretary of State through Development Consent Orders (DCO), with each round of DCO requiring some three years to allow for consultation, application, assessment, recommendation and final decision.
4. Coordination across the UK nuclear estate. A GDF must meet the requirements of all its end-users in terms of materials to be managed, waste acceptance time schedules, operational policy, technology and costs. Once a GDF site has been approved it will be essential to work closely with the waste producers to optimize the phasing of the waste disposal process.

3. Waste inventory and its decay behaviour

As a consequence of its pioneering development of nuclear technologies since the 1940s the UK manages one of the largest and most complex higher activity waste inventories. It includes scores of waste streams destined for a GDF, and a significant stockpile of nuclear materials not yet designated by the Government as waste (e.g. plutonium, highly enriched uranium, spent fuel) (RWM, 2021). Illustrative designs for a GDF allow for some 750,000m^3 of packaged legacy wastes to be disposed of, roughly equivalent to a cube the height of the Queen Elizabeth Tower ('Big Ben'), London. In addition to these legacy wastes, a GDF in England or Wales will need to dispose of the higher activity wastes generated by the proposed fleet of new nuclear reactors announced by the Government in 2022 to improve national energy security. Furthermore the current interest in deployment of small modular reactors and advanced modular reactors could lead to a requirement to dispose of an extended range of waste types.

For the purposes of developing design concepts for a GDF the inventory is subdivided into High Heat-Generating Waste (HHGW) and Low Heat-Generating Waste (LHGW). The diverse isotopic compositions of the overall inventory means that it exhibits a broad range of activity levels and decay trajectories (Fig. 1). Modelling of the sum of the activity levels of the UK inventory shows it will decay to c.10^5 Terra Becquerels over c.100,000 years, equivalent to the radioactivity of the uranium ore used to fabricate it.

In considering the potential impacts on people of radionuclides disposed of in a GDF it is their radiotoxicity rather than their radioactivity that is most relevant. Radiotoxicity is a measure of the hypothetical radiation doses that would result if all radionuclides in a given amount of waste were to be dissolved in water (e.g. groundwater passing through a GDF) and ingested by people. This hypothetical approach allows comparison of how hazardous different types of disposed radioactive materials can be. HHGW and LHGW would decay to the radiotoxicity of naturally occurring uranium ore over 1000s years to 10,000 s years respectively (Chapman and McCombie, 2003; Verhoef et al., 2017).

4. Principal functions of a GDF

A GDF is a highly engineered, bespoke facility that, wherever it is constructed, fulfils dual safety functions (Chapman and Hooper, 2012):

- long-term containment of radionuclides such that they cannot migrate to the shallow subsurface in concentrations that could harm people and the environment; and
- deep isolation of higher activity waste from natural surface processes and from future human actions.

Essentially containment requires a technical solution that prevents harmful waste getting into the biosphere whereas isolation requires a GDF to be sufficiently deep such that it will not be affected by near-surface processes and/or future human activities. The role of the geosphere in delivering these key functions is to provide a stable cocoon protecting radioactive waste from the impacts of humans and natural processes such as glaciations, sea level changes and earthquakes, to provide a low-flux groundwater environment with geochemical conditions that minimise degradation of the engineered components of the GDF, and lastly to promote retention of mobilised radionuclides.

The details of the design of a GDF can vary significantly and need to be flexible to match the specific characteristics of the host rock and subsurface geological environment, the surface environment where it will be constructed, land use, community preferences, the nature of the waste inventory, and other constraints (International Atomic Energy Agency, 2011). For example, a GDF could be located beneath the sea bed or under the land surface; it could be accessed by shafts, an inclined ramp or both; disposal tunnels and caverns might be on one or several levels, and it might typically be constructed between a few hundred and a thousand metres depth. Furthermore, the nature of the full inventory of wastes to be disposed of is not finalised, and will influence the design of a GDF.

A GDF in England and Wales will be at least 200 m beneath the surface where the geological environment is inherently stable and processes are generally slow. The 200 m–1000 m depth interval of interest allows for flexibility according to the disposition of suitable host rock formations, the increasing engineering and construction constraints with greater depth, and a minimum depth constraint based on the extent to which future glacial and climate evolution processes could affect the properties and behaviour of the shallower geological environment. Most other countries developing deep geological repositories plan to construct their GDFs between about 450 m and 650 m, although some are deeper (e.g. the GDF at Nördlich Lägern in Switzerland will be some 800 m deep).

NWS is mandated by the Government to monitor other technologies and disposal concepts but presently favours a GDF as the best solution for disposing permanently of the UK radioactive waste inventory

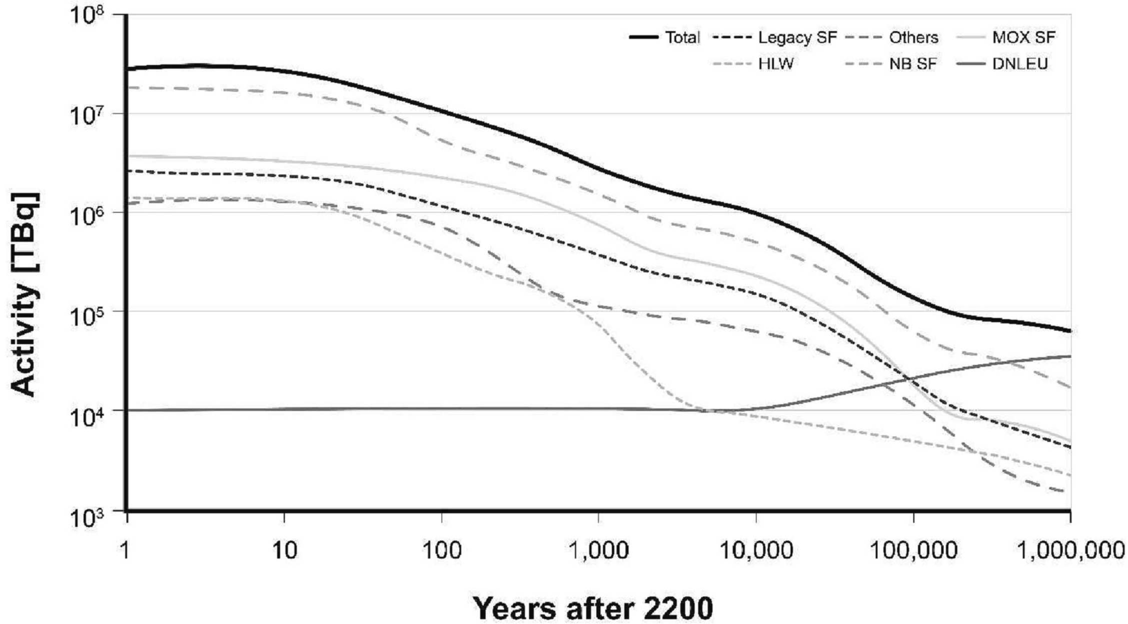

Fig. 1. Evolution of total activity of key waste groups in the Inventory for Geological Disposal. New build spent fuel dominates earlier activity whilst legacy spent fuel dominates later on. This is because shorter lived fission products will have decayed (reducing the activity of the spent fuels) whereas longer lived radionuclides (e.g. naturally occurring uranium isotope U-238) from DNLEU persist. The increase in activity of the DNLEU waste group is due to the growing-in of the shorter-lived daughters of uranium isotopes that are present in natural ore. From RWM (2021).
NB SF – new build spent fuel; HHGW – high-level waste; MOX SF – mixed oxide spent fuel; DNLEU – depleted, natural and low-enriched uranium.

(UKRWI). Between 2003 and 2006 a wide range of options on how to deal with the UKRWI were considered by the independent Committee on Radioactive Waste Management (CoRWM), from indefinite storage on or below the surface through to propelling waste into space. In July 2006 CoRWM recommended that geological disposal, coupled with safe and secure interim storage, was the best available approach for the long-term management of the UKRWI. CoRWM has restated its support for a GDF in its most recent work programme.

5. Role of the multibarrier system in containing the waste

In common with international approaches to deep geological disposal, the containment function of a GDF in the UK is provided by a combination of rock and engineering generally referred to as the multibarrier system. The fundamental principle underpinning multibarrier systems is that the engineered barriers – solid wasteforms, canisters, buffers, backfill materials, plugs and seals – are designed to work together with the rock to provide optimum conditions for long-term containment. This explains why the GDF Programme seeks to identify geological environments for which bespoke engineered barriers can be tailored to optimize the performance of the multibarrier system. It also explains why there does not exist a series of ready blueprints for implementing a GDF – the detailed design depends on surface and deep subsurface conditions at a GDF site where the nature of the deep geological environment, including the chemistry of deep groundwater systems, significantly influences the materials and designs that will be used in the engineered barriers. Whilst engineered barriers can be designed to work together with a broad range of rock properties and geological settings, there are constraints on what suitable geology might look like: it needs to provide a low-flux groundwater environment with geochemical conditions that minimise degradation of the engineered components of the GDF, to promote retention of mobilised radionuclides, and to exist at depths that will protect the waste from the impacts of humans and natural processes.

HHGW and LHGW disposal concepts have been used in the GDF Programme to show how the engineered barrier system could look in different geological environments (Fig. 2). These are based on generic geological environments and engineering concepts that have been developed in other national programmes.

In the Swedish KBS-3 concept developed for spent fuel disposal (SKB, 1983) and currently being used in Finland for the construction of what will be the world's first GDF for used reactor fuels, the fuel assemblies are packaged in 5 cm-thick copper canisters with the lid hermetically sealed. In gneissic host rocks, canisters are emplaced in a 30-40 cm-thick jacket of highly compacted bentonite in vertical drill holes. They are spaced such that the rock can conduct away heat generated by the spent fuel without adversely affecting the properties of either the engineered barriers or the host rock, drill hole spacing being determined by the type of fuel and canister loading, and the thermal properties of the rock (Sundberg, 2017). As the GDF saturates with groundwater during the early post-closure period expansion of smectitic clays in the bentonite creates high swelling pressure (2 MPa–10 MPa) forming a low-permeability seal between the canisters and the rock, thereby isolating the copper from sulphate-reducing microbial activity (Haynes et al., 2021). Disposal tunnels are backfilled with bentonite and rock spoil, and concrete plugs and seals isolate tunnels entrances and access ways.

LHGW does not generate a significant amount of heat, so packages do not need to be widely spaced and the caverns in which they are placed therefore occupy less 'footprint' per unit volume of waste than HHGW. Illustrative UK disposal concepts show disposal vaults in which stillages containing four 500 l stainless steel drums are stacked in multiple storeys. The vaults are backfilled with a high-porosity, highly alkaline cement encasing the stillages, with their entrances sealed by concrete plugs.

LHGW generates gas due to water radiolysis, corrosion and organic decay and cannot be packaged in hermetically sealed canisters. The stainless steel drums will degrade over the early post-closure period of the GDF (decades to tens of thousands of years), such that their contents migrate into and interact with the cementitious backfill whose primary functions are to retard radionuclide migration by sorption onto pore surfaces, filter radionuclide containing colloids, and create a high-pH environment in which radionuclide solubility is minimized, with an

Fig. 2. Schematics of disposal concepts for High Level Waste (High Heat Generating Waste, left side) and Intermediate Level Waste (Low Heat Generating Waste). Insets give perspective views of a geological disposal facility with HHGW occupying the larger footprint despite that it comprises a volumetrically smaller component of the UK higher activity waste inventory. This reflects the need to space HHGW canisters further apart to allow heat to be wicked away by the rock. The disposal concept for HHGW depicted here shows it packaged in copper canisters that are being emplaced in vertical boreholes within a bentonite buffer separating the copper canisters from rock. Contrastingly LHGW is packaged within vented stainless steel drums, contained four apiece in casks stacked within a vault that will be backfilled and sealed once it is full.

extensive buffering capacity capable of maintaining these conditions for tens of thousands of years (Hoch et al., 2012).

6. Natural analogues

Use of natural, historic and archaeological analogues (e.g. Miller et al., 2001) has proven to be an instructive tool for explaining to communities and other stakeholders how a GDF provides long-term containment as well as being a source of technical information on the corrosion behaviour of materials similar to those used in the engineered barrier system, and on the behaviour of radionuclides in the natural environment over thousands to millions of years.

Oil and gas field caprocks help to explain how low permeability formations can provide long-term containment. A key ingredient of major petroleum provinces is often thick and extensive intervals of rock salt and/or low-permeability mudstone, similar to some of the lithologies identified as potential GDF host rocks. They are proven to act as effective barriers to fluid movement because they have prevented buoyant hydrocarbons escaping to the surface, sometimes for millions of years (Gluyas and Swarbrick, 2021).

Natural analogues can also be used to illustrate how engineered barriers interact with the rock in which a GDF is constructed to maintain long-term containment. For example mineralization associated with a natural hyperalkaline plume at Maqarin, Jordan is analogous to crack-healing processes that would occur in a GDF due to interactions between cementitious buffer materials and groundwater solutes (Watson et al., 2011).

At the scale of a GDF perhaps the most widely cited analogue is at Cigar Lake, northern Saskatchewan, a high-grade uranium ore body. The ore deposit is around 1.3 billion years old, is located at some 430 m depth and is encased in claystone. No radiometric trace of one of the world's richest uranium deposits has been detected in the overburden nor at the present surface suggesting that the claystone has acted as a natural permeability barrier preventing radionuclides migrating into the far-field environment (Smellie and Karlsson, 1996). On its own Cigar Lake does not demonstrate that the geological component of a multi barrier system will adequately protect people and the environment, and waste management organisations such as NWS do not use Cigar Lake to show how a GDF might look and function. But it is useful for building confidence in the principles of long-term isolation and containment.

7. Building a safety case for a GDF

The post-closure period over which the England and Wales independent regulators will require a safety case to demonstrate the long-term containment and isolation capabilities of a GDF is up to 1 million years (OECD, 2009). The long timescales makes post-closure safety assessments a unique feature of deep geological disposal programmes as they need to take account of future natural and anthropogenic processes taking place over timescales that can be equivalent to a half of the Pleistocene epoch.

Performance and safety assessments must show that calculated radiological risks from any projected releases of radioactivity are very low with target levels being set by regulators that are far below those from normal radiation exposures to people (SKB, 1999; Environment Agency and Northern Ireland Environment Agency, 2009). As shown by assessments in other advanced national disposal programmes the risks posed by such releases at any time in the future are indeed considerably lower than those caused by the natural background radiation to which we are all exposed. These assessments show that the main period over which the protection provided by a GDF is most important (as the potential risks are highest, although still extremely small) are within the first few thousand years after a GDF is closed. This is because radiotoxicity and therefore hazard potential (the capacity to cause harm if direct exposures or releases occur at that time) diminishes with time (Fig. 1) That disposal systems can be designed that are able to provide such effective protection over the earlier post-closure times explains why the peak impacts are calculated to occur at much later times: when in any case engineered containment can no longer be relied on, when natural processes inevitably lead to releases, but when decay has done much to attenuate the impacts of the most active, shorter-lived radionuclides.

Some countries require only qualitative estimates of impacts at long time scales (e.g. after 100,000 years) because it is considered that the uncertainties in model assumptions used in making quantitative estimates of impacts render the numbers of little realistic value to compare against health-based standards that can be used sensibly to manage and control well-characterized exposures. At these distant times, provided there are no major natural releases (and the system is designed to be highly robust against such possibilities), it is better to rely on broader comparisons e.g. of the anticipated small, low fluxes of radioactivity from the repository in the context of natural environmental fluxes or concentrations.

The environment agencies responsible for regulating the disposal of radioactive waste in the UK set the standard of environmental safety as a risk guidance level which requires that the radiological risk (of death or serious hereditary health impact) from a GDF to a person representative of those at greatest risk must be $\leq 10^{-6}$ per year (Environment Agency and Northern Ireland Environment Agency, 2009 op. cit.).

Radioactive waste should be disposed of in such a way that the radiological risks are as low as reasonably achievable under the circumstances prevailing at the time of disposal. The developer of a GDF should assume that human intrusion, with or without knowledge of the location of a facility and the nature of its contents, is highly unlikely to occur but practical measures should be implemented that might reduce this likelihood still further.

For the GDF Programme environmental safety cases will be structured as a series of primary safety claims, supported by multiple arguments, themselves informed by experimental and observational evidence, that are used to demonstrate clear understanding of a GDF in its geological setting as it evolves. The safe performance of a disposal system cannot depend on human intervention beyond a few hundred years, nor on any engineered system requiring the operation of electrical circuits or mechanical moving parts. This is sometimes known as passive safety and it places reliance on a combination of engineered measures and natural features: the multibarrier concept.

International databases have been compiled listing all significant features, events and processes (FEPs) that might be claimed or assumed to impact the performance of a GDF (Capouet et al., 2019). Site-specific geosphere FEPs will exert a fundamental influence on the design of a GDF. Features are physical components of the disposal system and environment, such as rock properties and groundwater chemistry. Events are dynamic interactions between features that are short compared to the safety assessment timeframe, such as earthquakes and continental glaciations. And processes are dynamic interactions among features that generally occur over a significant proportion of the safety assessment timeframe, such as changes in redox interfaces and viscoplastic creep in rock salt.

All of the FEPs described here are potentially relevant to GDF siting decisions. Sites are evaluated consistently under six overarching headings, three of which are impacted by the geological setting – safety, engineering feasibility and value for money. “Suitable” geology is that which is safe during the operational and long-term post-closure period, which could have a GDF and its accessways constructed within it, and which delivers value for money. Whether each of the FEPs described here become important for future siting decisions will depend on the location of individual sites and their particular characteristics, including the geological setting.

8. Building confidence in knowledge of the subsurface environment

Uncertainty is inherent in site characterization because subsurface investigation techniques inevitably produce an incomplete picture of the distribution and properties of rocks and fluids. Management of subsurface uncertainties is a process that continues throughout the life of a GDF, from siting and construction through operation and decommissioning. These uncertainties are reduced throughout the life of a GDF but need to be understood and managed in each stage of its delivery (Diaconu et al., 2023). Early identification of critical uncertainties enables a programme of activities to be put in place that targets reduction of uncertainties to a level such that their associated risks can be mitigated.

The design of a GDF will depend on surface and subsurface conditions at a potential site. The nature of deep geology, including the chemistry of deep groundwater systems, exerts the strongest influence on the optimization of the design and materials that will be used for the various elements of the engineered barrier. Before regulatory approval of a site is achieved, and a community has signified its willingness to proceed to GDF construction, detailed site characterization will be used to increase knowledge and confidence in understanding of the subsurface, select and refine an appropriate GDF concept and design, and reduce uncertainties in the overall GDF Programme.

Managing and communicating uncertainty can pose a challenge to incorporating understanding of the subsurface into a siting programme and a GDF safety case. Uncertainty can exist in both the data and in the selection of the most appropriate approaches used to describe, model and interpret the behaviour of the rock-groundwater system, and it often arises from the limited observations that are possible from a site characterization.

Three broad categories of subsurface uncertainty need to be managed in the GDF Programme:

- Rock availability – host rock depth, thickness, areal extent and compartmentalization;
- Properties and behaviour of the deep environment – required to produce a robust operational and post-closure safety case; and
- Constructability and operability – suitable rock properties that enable construction and operation of a GDF, including its surface to subsurface access ways.

Quantification of uncertainty generally requires expert judgment. There are well-developed techniques for accessing expert judgment and incorporating it into decision-making procedures, for design and safety case development and strategic project decisions. These will be adapted to and implemented for a GDF as work progresses though the different stages of site selection, design, construction and operation leading to final closure.

Effective communication of uncertainty and risk to different stakeholders can be challenging (e.g. Flynn et al., 2001) and there are often differences between scientific and public perceptions of risk (e.g. Sjöberg et al., 2004). For high-profile projects like the GDF Programme it is very important to understand the issues and uncertainties that stakeholders take into account when evaluating risks and which can lead to these differences. It will be essential throughout the GDF Programme to engage communities in conversations about uncertainty and to explain how it is being managed (brokering matters of concern rather than conveying matters of fact: Stewart and Lewis, 2017).

9. Site characterization

A site cannot be sufficiently characterized and all uncertainties adequately addressed in a single phase of information-gathering. Improving confidence in the description of the subsurface environment is by nature a staged process and site characterization activities are organised such that they can enable informed decisions to be made at the appropriate points in the programme. At its present early stage, where understanding of potential GDF sites is limited to the geoscientific data already available and the range of options for GDF design is therefore wide, site characterization is focused on knowledge gaps around the likely availability of suitable rock volumes such as potential host rock depths, thicknesses and areal extents. In lower strength sedimentary rocks for example these questions can be addressed by high-quality 3D seismic data integrated with existing borehole data from oil and gas exploration. Where early site characterization activities indicate the likelihood of available volumes of potentially suitable rock in areas where local communities are fully engaged with the GDF Programme, information from dedicated, targeted boreholes will subsequently be needed. As the only means of direct sampling of rocks and groundwater in the deep subsurface, borehole data will be the prime source of information enabling detailed understanding of issues around post-closure safety and GDF constructability and operability.

The evolving understanding of the subsurface will be captured in several iterations of site descriptive models (SDM), a comprehensive suite of 3D models, reports and numerical simulations that contains the aggregated knowledge of a specific site, particularly how its deep geology contributes to long-term safety. SDMs underpin designs and safety cases, and early versions will be used to support applications for permission for subsequent deep borehole drilling. Each version of a SDM represents the endpoint of one cycle of targeted data acquisition, interpretation and synthesis. Site-specific design and safety assessments based on SDMs are used to define further information requirements. SDMs will be updated iteratively allowing testing of earlier predictions against information obtained from new boreholes, long-term downhole tests, and eventually underground excavation and construction.

Site descriptive models are a vital part of the characterization process and whilst they offer an agreed foundation to build on for the next iteration of analysis or design, it is the information that is not known, and the information with an unacceptable level of uncertainty, that will drive the nature and scope of future investigations.

Some uncertainties can be significantly reduced whilst others cannot: some will be mitigated by engineering and design, but a few are irreducible and will need to be incorporated into the range of inputs and outcomes in safety case evaluations. A widely applied depiction of uncertainty shows it occupying the gap between converging 'Information and Understanding' and 'Uncertainties and Options' curves (Fig. 3). In this scheme the shapes of the curves express different 'uncertainty trajectories' that vary according to, for example, the complexity of a site being characterized. For GDF site characterization a more realistic representation of uncertainty incorporates step increases in information/reductions in options with successive inputs of new data – legacy regional data, reconnaissance 2D then 3D seismic data, deep investigative boreholes, deviated boreholes, reprocessed seismic data, underground mapping, sampling and testing, etc.

10. Geological features that contribute to containment and isolation

10.1. Rock material properties

The nature of the material properties of rock types in which a GDF could be constructed (host rock) informs all three high-level subsurface uncertainties – rock availability, properties and behaviour of the deep environment, and GDF constructability and operability.

In common with international practice three broad categories of host rock type are recognized – rock salt, lower strength sedimentary rocks (LSSR) and higher strength rocks (HSR). Fig. 4a, b, c show their distribution within the 200-1000 m depth interval of interest in England and Wales. In seeking communities with which to engage in the GDF siting process NWS has no preference as to which of these three categories of host rock are present in a potential area of interest. A GDF in England and Wales could be constructed in any of them, with each rock type category presenting different technical challenges. GDFs are being planned by overseas waste management organisations in all three rock type categories.

The area of interest in which a GDF could be constructed includes an inshore zone up to 12 nautical miles (c.22 km) from the coast. Should a

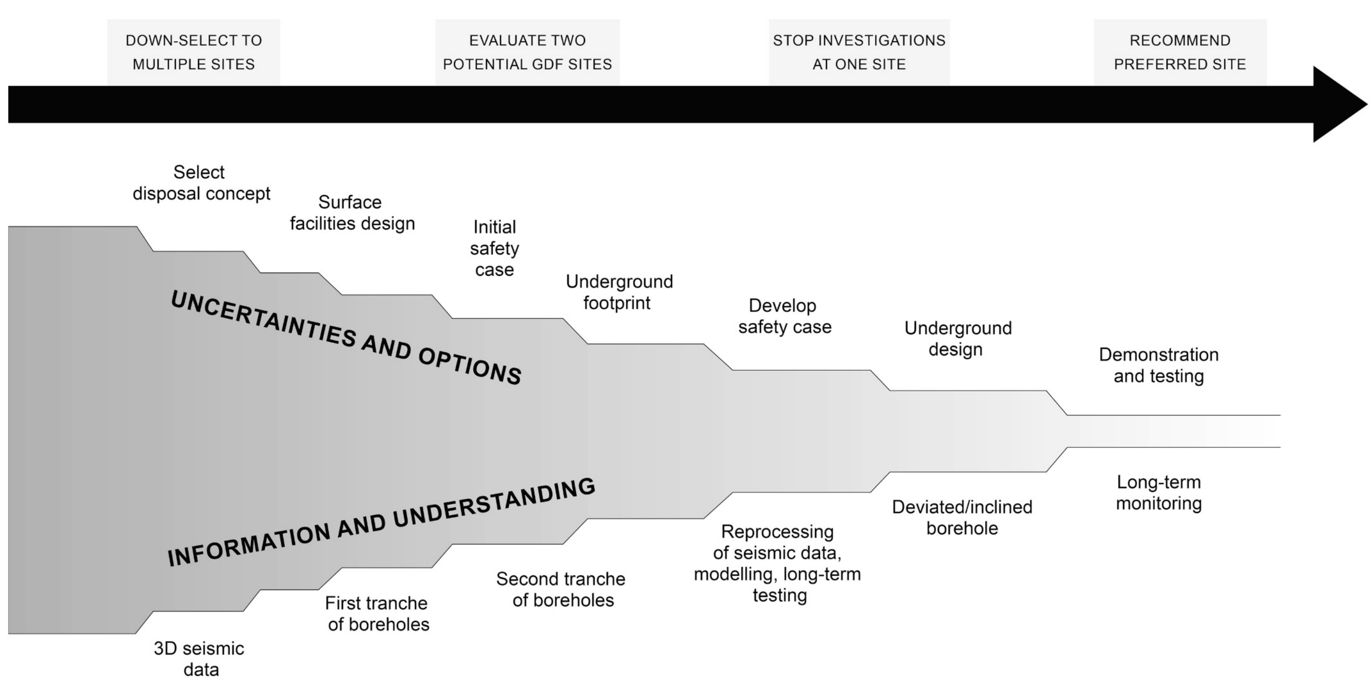

Fig. 3. Information and Understanding vs. Uncertainties and Options funnel depicting how the range of options for a major infrastructure project like a geological disposal facility (GDF) reduces through successive phases of information-gathering and synthesis. The trajectories are stepped, each step coinciding with the increased understanding resulting from a new tranche of subsurface data. Note that the lines converge but never join, the gap representing residual uncertainties that are irreducible or too small to affect the project materially.

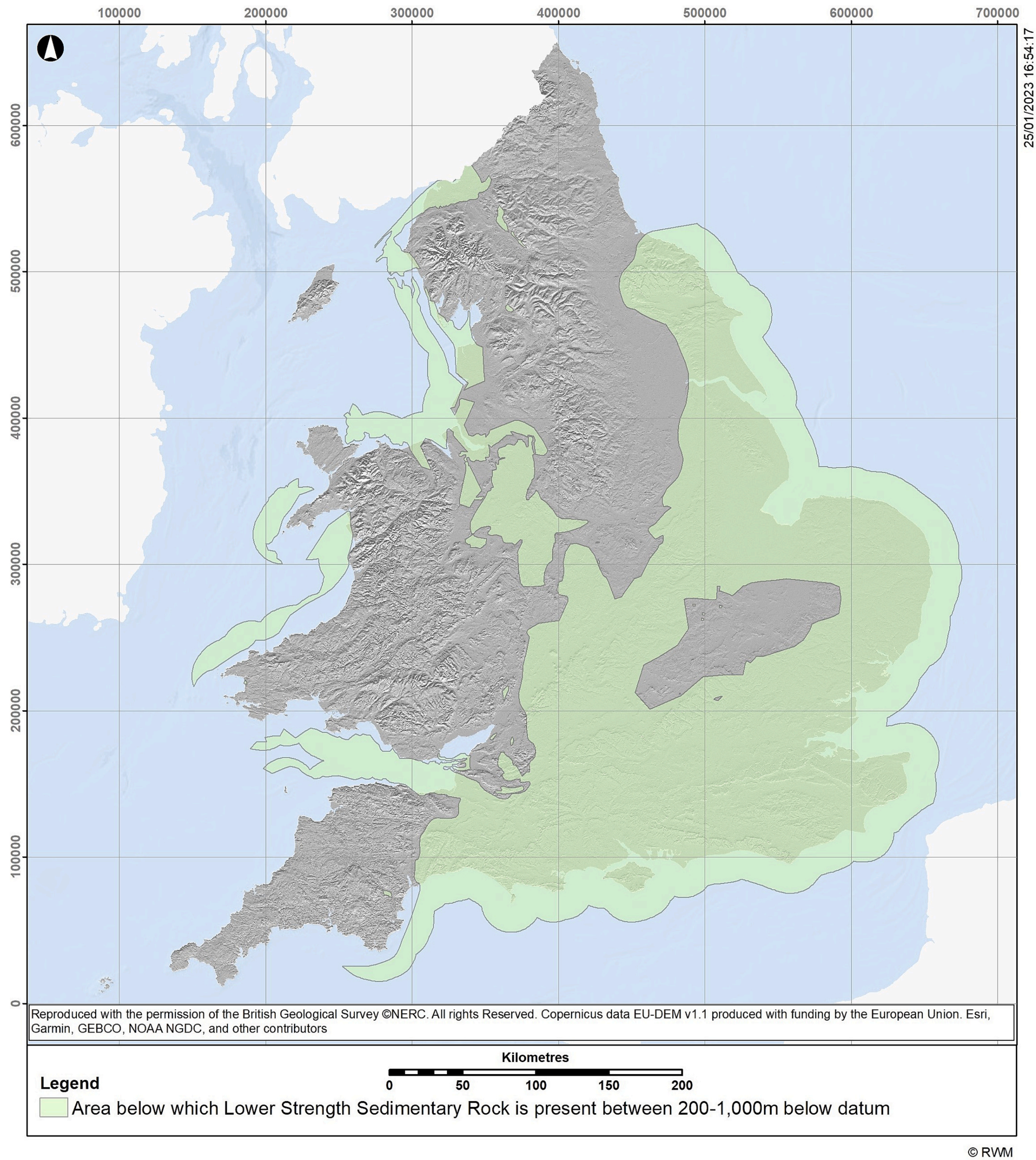

Fig. 4. Presence of Lower Strength Sedimentary Rocks (LSSR – 4a), Evaporite (4b) and Higher Strength Rocks (HSR – 4c) within the 200 m–1000 m depth interval of interest in England and Wales, superimposed on a digital elevation model. LSSRs extending beyond the coastline are shown out to the 12 nautical mile limit. In areas of high topographic relief maps produced using depths of 200 m and 1000 m below datum will include volumes of potentially suitable host rocks beneath hills and mountains. In places these rocks would therefore be located at >200 m depth below ground level and a geological disposal facility constructed in them could be accessed by a horizontal or gently inclined tunnel excavated into a hillside. Details of how this map was produced are given in RWM (2016), including the definitions of LSSR and of the depth datum.

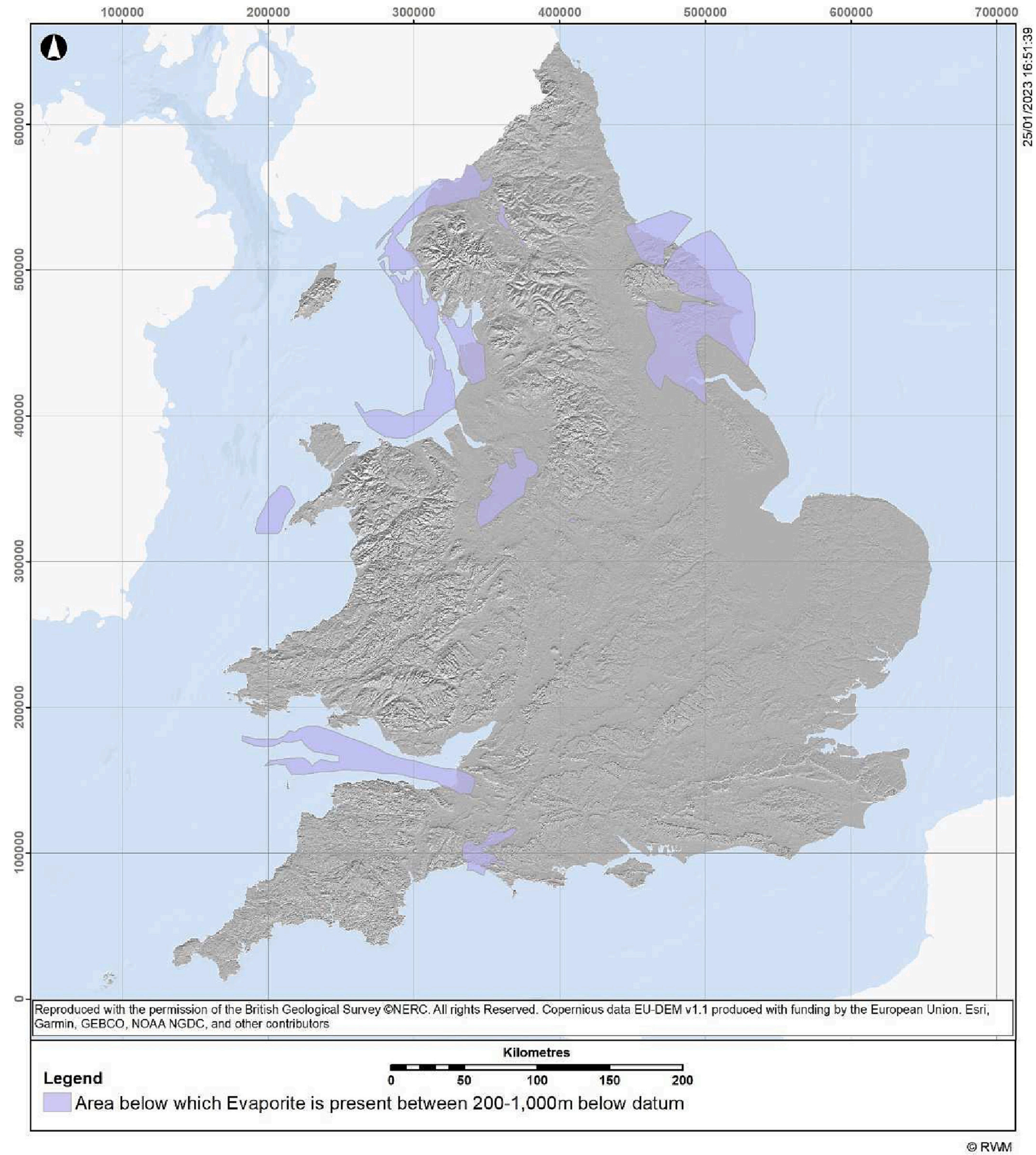

Fig. 4. (*continued*).

GDF be located beneath the seabed it would be accessed via an inclined ramp, or drift, originating at a surface site near the coast. Knowledge of the nature of rock properties and geological structure of the overburden of a GDF would therefore be important for the post-closure and operational safety cases for the GDF disposal zone and the access ways along which nuclear materials would be transported underground.

10.1.1. Rock salt (halite)

Halite contains almost no free water and its interlocking crystalline texture means it exhibits near-zero porosity and permeability. In England and Wales halite forms part of evaporitic successions within the Late Permian Zechstein Group and the Late Triassic Mercia Mudstone Group. Preservation of >200 million-year-old halite in the UK is testament to the absence of significant volumes of fresh water moving through the subsurface environment. The visco-plastic rheology of halite

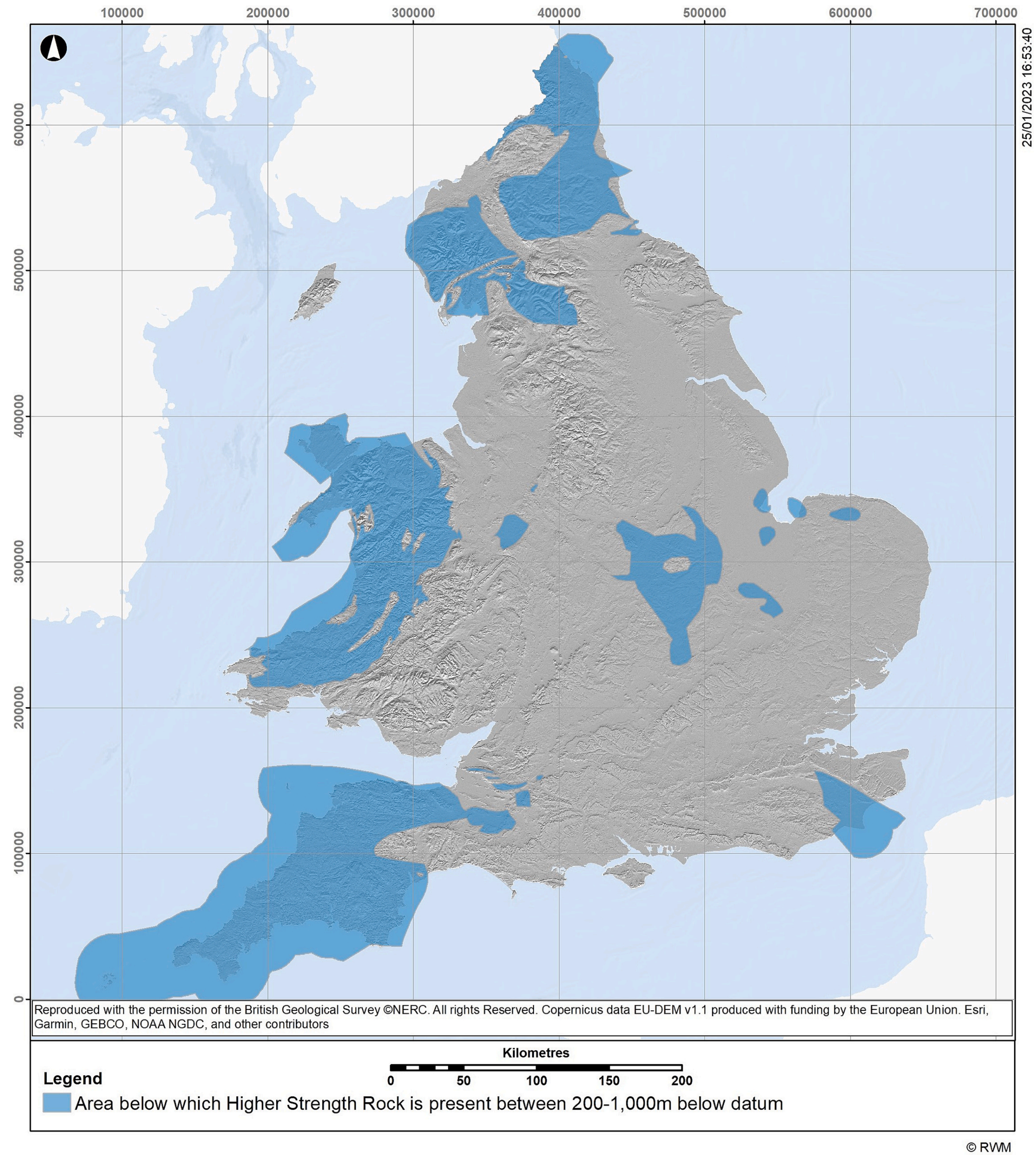

Fig. 4. (*continued*).

under the confining pressures encountered hundreds of metres below the surface means that brittle fractures would heal and any small unfilled excavated openings would close relatively rapidly (Chen et al., 2013). Halite is mechanically weak and could require significant reinforcement, depending on the duration of the operational phase of a GDF. Its tendency to creep means that during the early post-closure assessment period halite would progressively close in on disposal vaults and tunnels, eventually sealing them within the rock mass.

Halite and other evaporite minerals can occur in both bedded formations and diapiric (dome) structures. In the England and Wales onshore and inshore area halite occurs only in bedded formations and does not form domes, salt walls or intrusive diapiric structures. GDFs in salt domes are in operation in Germany, a country which also disposes of considerable quantities of hazardous industrial wastes in disused salt mines (Fig. 5). The Waste Isolation Pilot Plant, New Mexico, USA is constructed in a 550 m-thick bedded halite of Permian age.

Fig. 5. Waste disposal operations at the ERAM repository constructed inside a Permian salt diapir at Morsleben, Germany. Photo courtesy: Bundesgesellschaft für Endlagerung mbH.

The GDF environment in a halite could be so dry that gas generation due to radiolysis of contained aqueous fluids would be very limited. However pressure build-up cannot be discounted. Evidence from halites and claystones suggests that gas could create micro-pathways (micro-fissures) along grain boundary openings at pressures below fracture pressure at which macro-scale pneumatic fractures form (Popp and Minkley, 2007, Urai and Spiers, 2017, Wiseall et al., 2015).

10.1.2. Lower strength sedimentary rocks (LSSR)

In all four of the areas in which Community Partnerships have been established to date, LSSRs have been identified as potentially the most suitable host rocks in which a GDF could be constructed and they are being targeted for further evaluation. However England and Wales policy requires NWS to evaluate the suitability for a GDF of all areas brought forward through the volunteer siting process, with no preference for particular geologies.

A range of LSSRs is also the focus of GDF siting programmes in several European countries (Table 1). Mesozoic mudstones are the LSSRs of greatest interest as potential GDF host rocks in the UK (Palaeogene claystones such as the London Clay Formation are generally not buried deeply enough as the minimum depth limit for a GDF is 200 m). The fine grain size and high clay mineral composition of LSSRs means that whilst bulk porosity may be quite high (e.g. Opalinuston up to 20%: Bossart and Thury, 2011), permeability is so low that diffusion would be the dominant process of any potential radionuclide migration from a GDF.

The rheology of many Jurassic-Cretaceous LSSRs is such that open fractures which form within the rock volume (e.g. by tunnel excavation) would heal during the early post-closure period. Fracture healing processes in LSSRs that might host GDFs are the subject of ongoing research in underground rock laboratories. French and Swiss GDFs are planned to be constructed in Callovian-Oxfordian and Aalenian claystones respectively, formations that are thought to possess comparable gross architecture and rock properties to the Middle Jurassic claystones of southern Britain.

In the 200-1000 m depth interval of interest for a GDF, the Triassic sub-basins of the western UK contain a heterolithic succession of mixed mudstone, siltstone, sandstone and halite known as the Mercia Mudstone Group (MMG). The Middle to Late Triassic MMG is a synrift sequence that accumulated in a semi-arid depositional environment dominated by playa lakes, flash floods and aeolian processes. Its diagenetic history means that the clay mineral component of mudstone-dominated intervals is less than many younger claystone formations (Hobbs et al., 2002).

The distribution of the MMG is largely controlled by the Triassic rift architecture and it contrasts markedly with Jurassic-Cretaceous LSSRs in its lithostratigraphy, structure, rock properties and heterogeneity. Unlike Jurassic-Cretaceous LSSRs the MMG accumulated in fault-controlled basins, often exhibiting marked facies changes across syn-depositionally active faults. Following the cessation of rifting in the Late Triassic, the MMG was buried beneath several kilometres of post-rift sediments before its exhumation due to regional uplift and erosion in the mid-Cretaceous and Palaeogene. Because the MMG has generally formerly been more deeply buried by around 2-3 km (Hillis et al., 2008) its elastic properties are stiffer and more brittle than would be expected for rocks in the 200-1000 m depth interval. Former deeper burial of the MMG means it exhibits overcompacted mechanical properties and the assumption that LSSR fractures self-heal may not apply.

The MMG is an effective barrier to hydrocarbon migration and provides the caprock for several major fields, most notably Wytch Farm in southern England, formerly the largest onshore oilfield in western Europe and with a significant gas cap (Gluyas and Swarbrick, 2021).

Rates of gas generation in the wastes and engineered materials in a GDF may be limited due to the supply of water from a LSSR host rock (Towler and Bond, 2011). Relatively high gas entry pressures in LSSR

Table 1
Summary of rock properties for a range of Lower Strength Sedimentary Rocks being considered as host rocks for European GDF Programmes. All unreferenced parameters are taken from NEA (2022).

LSSR (country)	Age (Ma.)	Depth to top (m)	Thickness range (m)	Uniformity (km)	Heterogeneity Lateral/ Vertical	Heterogeneity (High-Medium-Low)	Porosity (%)	Hydraulic conductivity (m/s)	Total clay (wt%); Plasticity (High-Medium-Low)	Uniaxial compressive strength normal to bedding (MPa)
Boom Formation – (Mol, Belgium)	Oligocene (32–28)	190	[11]105	≥100 – continuity over long distances mappable on a national scale	four consistent members including the Boom Clay mappable across the sequence, varies according to CO3 and organics	Low	[11]35–41	4.7×10^{-12} in situ	25–71 High	2
Kortrijk and Tielt Formations, (Kallo-Doel area, Belgium)	Eocene (55–51)	289–329	[11]110	≥150	consistent members mappable across the sequence, several clayey members	Low	[11]30–48	[11]10^{-9} in situ	25–65 High	1.3
[12]*Callovian-Oxfordian (Bure, France)*	Middle to Upper Jurassic (163–158)	490	[6, 11]130–150	≥200	[12]laterally homogeneous, argillaceous to marly limestone	Medium to Low	[6]14–21 [9]13–17.8	1.9×10^{-13}	29–49 Medium	26 ± 6
Oxford Clay Formation (England)	Middle to Upper Jurassic (166–157)	surface to >500	[3]50–70 (≤185); [11]70–110	10s	[7]10s km–[8]10s m	Medium (fairly consistent within members but varies from silty claystone to claystone UK-wide)	[4]20–36 (Harwell); 22–55 (Winterbourne, Kingston); 20–64 (Southampton)	[5]min/max/av. 1.09×10^{-10}/ 1.07×10^{-9}/6×10^{-10}	[14]45–49 (Peterborough Member) Low to Medium	[4]average 2.4 (Harwell)
Opalinuston (Mont Terri, Switzerland)	Middle Jurassic (172)	220	[10]90–160–160	≥100	[13]homogeneous formation with only minor vertical and lateral lithological variability	Low	13.7	3.1×10^{-13}	[15]10–25 Low to medium	7–16
Opalinuston (NE Switzerland)	Middle Jurassic (172)	540–830	[11]100–130	≥100	[13]homogeneous formation with only minor vertical and lateral lithological variability	Low	10.9	8.0×10^{-14}	[15]10–25 Low to medium	31
Mercia Mudstone Group (England & Wales)	Permo-Triassic (252–201)	surface to >900	[2]330–1485 in Cheshire	<1–50	100 s m/10s m	High (between and within nine sub-basins)	[1]7–12	[2]10^{-9} –10^{-11}	[2]10–40 Low to Medium	[2]0.2–10

[1] Armitage et al., 2016.
[2] Hobbs et al., 2002.
[3] British Geological Survey, 2020.
[4] Horseman et al., 1982.
[5] Pierpoint, 1996.
[6] Armand et al., 2013.
[7] Ferry et al., 2007.
[8] Armand et al., 2017.
[9] Menaceur et al., 2015.
[10] Bossart et al., 2018.
[11] Boisson, 2005.
[12] Trouiller, 2006.
[14] Norry et al., 1994.

mean it would be difficult for free gas phases to flow from a GDF through undisturbed rock. However depending on the combination of gas generation, water inflow and gas migration in solution, gas could be released from a GDF through dilation and micro-fissuring. These pathways are expected to heal upon water resaturation.

The MMG is identified as potentially the most suitable GDF host rock in the three Community Partnerships with which NWS is presently engaged in Cumbria, NW England whereas Middle Jurassic Ancholme Group claystones are being targeted in the Theddlethorpe Community Partnership, Lincolnshire, eastern England. Detailed evaluation of these four areas commenced in 2022 with no decisions based on technical assessments due until 2026. However among the principal challenges associated with these sites will be the greater heterogeneity of the MMG compared to the Ancholme Group. This arises largely because the difference in their depositional settings. The MMG is characterized by marked vertical and lateral changes in sedimentary facies and rock composition over short distances. Contrastingly the Ancholme Group comprises a package of laterally persistent, mudstones and claystones that blanketed much of NW Europe. Rocks of similar age and facies to the Ancholme Group will provide the host rock for a GDF that will be constructed by ANDRA in the eastern Paris basin.

10.1.3. Higher strength rocks (HSR)

Typical HSRs in England and Wales are igneous rocks, volcaniclastics, metasediments, slate and highly compacted, formerly deeply buried Palaeozoic sedimentary rocks. Because they tend to be older than most LSSRs and rock salt intervals, many HSRs have experienced multiple episodes of regional tectonic deformation. High levels of compaction and metamorphism of HSRs means they are mechanically strong and therefore usually contain networks of open fractures through which fluids can move advectively. Matrix permeability in most HSRs is low and rock matrix diffusion has been shown to be potentially less significant in retarding radionuclide migration than previously thought (Wogelius et al., 2020). Swedish and Finnish spent fuel repositories are being constructed in Archaean granitoid and gneissic HSRs.

Understanding and predicting groundwater flow in many HSRs is complicated by their inherent heterogeneity. Structural complexity, spatially variable petrology and complex fracture networks typical of HSRs means that development of three-dimensional hydrogeological models can require a high density of investigative boreholes. Establishing the role of major faults and fault zones as conduits and/or barriers to groundwater and free gas flow can be challenging and, in some volcaniclastic successions, the presence of volcano-tectonic faulting adds complexity (Branney and Soper, 1988; Branney and Kokelaar, 1994). It can be difficult to initially constrain the number of boreholes required to characterize groundwater heads, flows, and geochemistry in HSRs. Consequently site characterization of terranes containing potential HSR host rocks may be protracted and staged to ensure that sufficient data have been acquired to adequately characterize spatial variability and hydraulic conditions.

Seismic reflection and other geophysical methods are generally poor at imaging HSR because interfaces between different lithotypes are often more steeply inclined, more complex, and because impedance contrasts across them tend to be lower. Characterizing HSRs to investigate their potential as a GDF host rock would therefore be largely dependent on boreholes. Iterative programmes of work developing the ability to develop a sufficiently representative model to describe groundwater movement in the fracture network has been a core activity in the Finnish and Swedish GDF programmes and has required considerable amounts of information from both boreholes and deep excavations.

10.2. Structural geometry and deformational features

This section discusses how the nature of deformational structures from the micro- to macro-scale could be a significant factor in siting and designing a GDF. Structural phenomena such as faults and fractures, folding and tilting can influence rock availability (particularly structurally controlled compartmentalization), the ability to produce safety cases, and GDF constructability.

A wide variety of geo-tectonic settings is potentially suitable for a GDF (Fig. 6). The geological evolution of England and Wales is dominated by structures that formed during repeated cycles of crustal stretching and continental collision in the early Palaeozoic (Caledonian orogenesis, post-orogenic collapse), later Palaeozoic (Variscan collision and foredeep, Visean rifting), Mesozoic (Pangea breakup, proto-Tethyan rifting, mid-Cretaceous global compression), and Cenozoic (North Atlantic opening, Alpine intraplate shortening).

Because of their potential influence on design, layout and operational and post-closure safety, the following types of deformational structures are of greatest relevance to a GDF:

- faults and associated fault damage zones;
- folds on the scale of tens to thousands metres wavelength;
- zones where layering is regionally inclined; and
- fracture networks and discrete fracture zones.

10.2.1. Faults and fault damage zones

Several belts of faulting are apparent across England and Wales, characterized by distinct fault orientations (Fig. 7). The English Midlands and much of northern England comprise a complex network of faults related to Caledonian orogenesis, strike-slip movements in the Variscan foreland, and Visean to Triassic rifting. Central Wales is dominated by NE-SW oriented faults that originated in Caledonian forearc basins (Woodcock, 1984). Southern England and south Wales exhibit broadly E-W faults nucleated in the Variscan orogenic basement which largely controlled the pattern of rifting in the Mesozoic cover. Throughout southern England the E-W Variscan trend was 'inherited' by an extensive belt of Mesozoic rift basins, subsequently reactivated in response to Cenozoic N-S compression that affected the Alpine foreland of NW Europe (Butler and Jamieson, 2013).

Faults and associated fracture zones are self-similar natural phenomenon that obey power law relations of scale and frequency (Kim and Sanderson, 2005). They occur across many orders of magnitude of scale and are more or less ubiquitous in Earth's crust. A GDF siting programme does not seek to avoid faulted areas except for the very largest structures and/or the most complexly faulted terranes, but to characterize them in order to understand the impact they could have on compartmentalizing an otherwise extensive host rock, on operational and post-closure safety, and on the layout of a GDF including its accessways.

Faults and their associated damage zones are a particularly important consideration for characterizing a rock volume in which a GDF might be constructed because they can:

- compartmentalize the host rock thus affecting the extent and geometry of potentially suitable rock volumes;
- exhibit induced seismicity due to fault reactivation by perturbation of the ambient stress field during excavation and operation of a GDF (including emplacement of heat-generating waste);
- respond to post-glacial stress reorganisation, perturbing the state of critical stress (nearness of fractures to shear failure) leading to the possibility of seismicity affecting a nearby GDF (Steffen et al., 2022);
- act as both barriers to and conduits for fluid flow such that their long-term behaviour will need to be taken account of as part of post-closure safety assessments;
- present geotechnical challenges to the excavation of shafts and tunnels; and
- adversely affect the clarity of seismic imaging of the subsurface during site characterization.

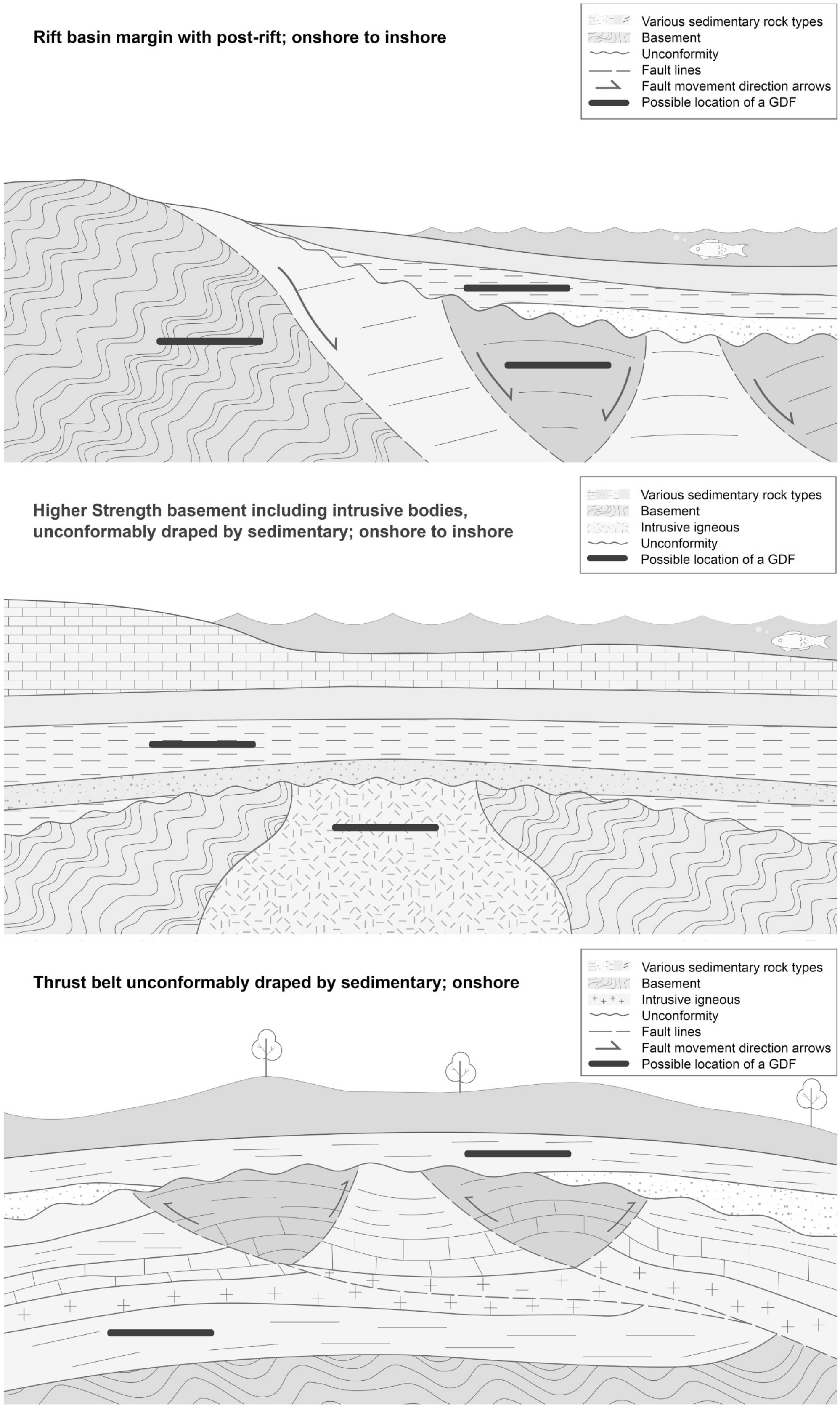

Fig. 6. Schematic cross-sections depicting a variety of geotectonic settings in which a geological disposal facility (GDF) could be constructed. GDFs are represented by the filled rectangles. No scale is implied although the depth interval of interest for a GDF in the UK is between 200 m and 1000 m.

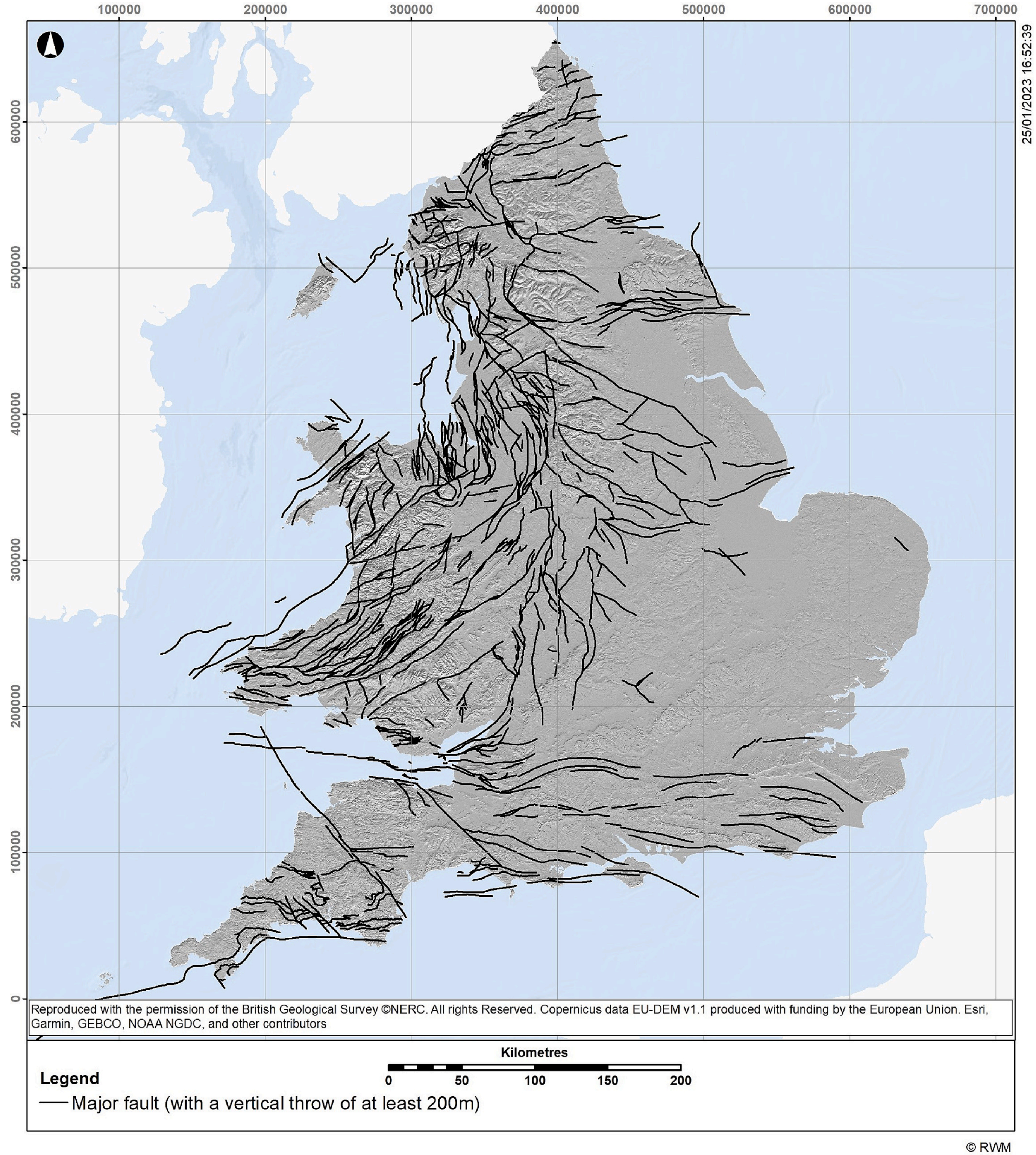

Fig. 7. Traces of faults with throws (vertical displacement) of at least 200 m, superimposed on a digital elevation model of England and Wales. Faults extending beyond the coastline are shown out to the 12 nautical mile limit. Details of how this map was produced are given in RWM (2016).

10.2.2. Folds and regions of inclined layering

In the Mesozoic and Cenozoic rocks of England and Wales zones of intense buckle folds are often associated with fault-related deformation, especially faults in southern England that were reactivated during Cretaceous and Late Palaeogene-Neogene (Alpine) compressional episodes. In Palaeozoic rocks intense folding is often more pervasive because it expresses accommodation of regional strain at deeper crustal levels. Longer wavelength folds (wavelengths of kilometres or more) can lead to inclined zones in which regions on the scale of the footprint of a GDF are characterized by uniformly dipping layers. Folds and inclined zones would need to be investigated in detail as part of site characterization.

10.2.3. Fractures

Fractures of principal relevance to GDF development are defined here as networks of small (typically metres to tens of metres length) brittle tensile cracks with no discernible offset. The main tectonic processes leading to deep fracture systems are curvature, far-field plate margin stress, and fault damage (elastic dislocations). Britain's complex tectonic history means different fracture generations overprint one another making it difficult to delineate areas of England and Wales with characteristic fracture types and orientations. Understanding fracture systems is particularly relevant in HSRs where fractures can be highly interconnected and provide the principal fluid migration pathways. In Finland and Sweden GDFs will be constructed in Archaean granitoid and gneissic rocks and the understanding gained from fracture network characterization and fluid flow modelling occupies a core position in their safety cases (Posiva, 2021a,b).

Sedimentary successions containing potential LSSRs could include relatively stiff lithotypes that contain fractures. Outcrop examples of the Mercia Mudstone Group in which gypsum crystals have grown into open fractures indicate that coarser grained units and/or evaporites sustain open fractures in the subsurface. However fractures in bedded sedimentary successions are often constrained by the geometry of the layers in which they occur, and the stress field that caused them is more homogeneous than it might be in a more massive HSR. Outcrop studies of layer-bound fractures show that one of the most common geometries is parallel sets of 'Mode 1' fractures aligned normally to the minimum principal stress, and/or X-, Y- and V-shaped Mode 2 and 3 fractures that intersect along the intermediate principal stress axis (Hancock, 1985). Consequently, fractures in layered sedimentary rocks often exhibit a more biaxial geometry and their connectivity may be significantly less than those in HSRs.

10.2.4. Characterizing deformational structures and predicting their impact on GDF performance

High-quality seismic data will enable an assessment of the potential for faulting to compartmentalize the rock volume available for GDF construction. Compared to the oil and gas industry whose seismic data are optimized to image depths of 3 km or more, the relatively shallow 200–1000 m depth interval of interest for a GDF means that seismic data should yield high-resolution imaging of faults of the order of a few metres throw. This would also allow characterization of the nature and extent of brittle fault damage such as fractures zones.

3D surveys obtained by Nagra from three layered sedimentary sites in northern Switzerland yielded high-resolution images of faults and fracture zones, particularly through the use of special attributes such as coherence and curvature (Nagra, 2019a; Nagra, 2019b; Nagra, 2019c). The behaviour of faults in a perturbed ambient stress field, and their long-term fluid flow characteristics, will be determined from modelling parameterized by fault zone properties obtained from core. As part of site characterization deep borehole drilling at each candidate site will include at least one deviated borehole designed to intersect fault zones and fracture systems.

In the event that claystone and/or rock salt sites become a focus for detailed site investigation, methods developed by the oil and gas industry will be adapted to understand fault sealing behaviour (Pei et al., 2015). Critical stress analysis (Sibson, 2017) will also be used to model how faults respond to natural and construction−/operation-induced perturbations of the stress field, including those triggered by post-glacial stress reorganisation and by emplacement of heat-generating waste.

10.3. Groundwater

Understanding groundwater properties and the controls over its movement, together with other processes by which radionuclides could migrate through engineered barriers and the geosphere, will be critical to demonstrating the long-term safety of a potential GDF site. Hydrogeological characterization will also be important to understand the ground in which shafts, adits or drifts might be constructed to access the deep repository zone.

10.3.1. Groundwater movement

Water is the main agent by which radionuclides could migrate into the surface environment. Long-term containment requires that a GDF should be constructed in a subsurface setting in which the flow of deep groundwater is absent (as in a halite formation), migrates only very slowly and/or is essentially isolated from shallow groundwater. A powerful line of evidence employed by several overseas waste management organisations to communicate long-term safety is the use of stable isotopes to demonstrate deep groundwater residence periods of hundreds of thousands of years in the vicinity of proposed GDFs (e.g. Nagra studies of $\delta^{18}O$, $\delta^{2}H$, Cl^{-}, He diffusion profiles across the Opalinus claystone: Gautschi, 2017). In the UK East Midlands 100,000-year-old groundwater has been recorded in pore spaces at 400 m depth in the Sherwood Sandstone Group aquifer (Edmunds and Smedley, 2000).

In the undisturbed geosphere the pattern of groundwater flow at a potential GDF site is determined by hydraulic gradients, rock properties and the properties of the groundwater. Sorption, precipitation and rock matrix diffusion (Wogelius et al., 2020) may retard radionuclide transport in groundwater whilst other phenomena such as complexation by organic matter or on colloids could enhance transport under certain conditions. The impact on the long-term safety of a GDF of eustatic and isostatic sea level change could be significant. In particular groundwater flow in low-lying areas could be affected by changes in hydraulic pressure gradients introduced by rising and falling base levels. Where there is no hydraulic gradient and/or where the permeability to water is very low diffusion may be the dominant transport process.

The hydraulic properties of the host rock and its environment control access of groundwater to, and movement of water in, the engineered barrier system. Cement-based engineered barriers can display either advective or diffusive solute transport through pore spaces and open fractures. The initial permeability to water of the cementitious backfill materials proposed for a GDF is low and will tend to decrease over time due to interaction with alkaline groundwaters and resultant calcite precipitation (Hoch et al., 2012).

The bentonite-based buffers used in HHGW and spent fuel disposal concepts have been selected for their high swelling pressure and low permeability following resaturation of a GDF (Gutiérrez-Rodrigo et al., 2015). Radionuclide transport in compacted bentonite buffers will occur by diffusion. Bentonite also has a high sorption capacity for some radionuclides and its small pore sizes means it is expected to preclude movement of colloids through the engineered barrier, and to limit the growth and mobility of microbes (Kurosawa et al., 1996).

Characterizing the nature and behaviour of groundwater in formations overlying a GDF will be a significant consideration in the design and location of accessways, where control of groundwater movement along the rock-structure interface and through the adjacent excavation damage zone will be essential.

10.3.2. Hydrogeochemistry

The integrated engineering barrier system needs to be optimized for present and future groundwater chemistry. Characterizing deep hydrogeochemical parameters (e.g. pH, Eh, salinity, groundwater composition) and understanding how they will evolve during the long-term post-closure assessment period is one of the most important tasks of the site investigation process. For example, copper canisters are an integral part of the spent fuel engineered barrier system in the Swedish KBS-3 concept, which requires long-term containment by the canister. However as copper is subject to corrosion in the presence of sulphur (Ollila, 2013; Rosborg, 2013), the content and chemical behaviour of sulphur compounds in groundwater need to be taken into account in performance assessments. For geological environments in which the groundwater could contain significant quantities of dissolved sulphates or sulphides, other canister materials would need to be considered if long-term resistance to corrosion is required. Note that the safety concept in a low-permeability, diffusion-dominated claystone environment might not require long-term canister longevity in order to provide the necessary containment, illustrating the balance of design requirements that need to be managed. A second example of the importance of hydrogeochemistry is the dependence of the behaviour of a bentonite buffer on groundwater salinity, with high salinities adversely affecting its swelling behaviour but low salinities adversely affecting its chemical erosion potential (Lee et al., 2012).

10.3.3. Microbes

Abundance of microbes in the subsurface is governed inter alia by groundwater flow and hydrogeochemistry, nutrient availability, and the introduction of anthropogenic materials into the natural environment. The characteristics of microbial populations are specific to local conditions but they can exist (up to 10^7 bacteria cells ml^{-1}: West and McKinley, 2002) in a broad range of rock types and the extreme thermochemical environments that can be encountered in a GDF, such as hyperalkaline cement porewaters and temperatures of several hundreds of degrees.

Microbes act as catalysts driving reactions to equilibrium using the energy released. Further work is required to better understand their impact on post-closure safety cases but the following processes are known to be microbially mediated (Humphreys et al., 2010; Meleshyn, 2014).

- Redox changes on clay mineral surfaces due to biofilm formation can enhance both precipitation and dissolution (i.e. positive and negative impact on fluid flow properties) and may affect the swelling properties of bentonite.
- Microbial metabolism is strongly influenced by redox chemistry and can affect wasteform dissolution rates and biogenic gas production, and in some circumstances may accelerate corrosion rates.
- Solute transport processes are influenced by microbial mobility and can alter radionuclide migration.
- Hydrogen and methane generated within GDFs may be subjected to microbial transformation as they travel through the geosphere. Hydrogen generated by radiolysis of the aqueous phase or by hydrolysis is commonly transformed to methane by methanogenic bacteria. Some methane may form directly through radiolysis of organic compounds in the host rock but this depends strongly on the extent to which the waste form emits gamma radiation.

10.3.4. Groundwater flow in fractured media

Understanding groundwater flow and solute transport processes in HSRs presents its own specific challenges because connected fracture networks allow fluids to flow advectively, and because some radioelement transport may occur both by advection and diffusion in the rock matrix. Fractures also provide spaces in which chemical reactions in groundwater can take place. Groundwater transport processes in dual-porosity (i.e. fractures and matrix) HSRs have been investigated in detail in Finland and Sweden. The investigators have used data from boreholes and underground excavations to develop and validate stochastic flow and transport models in fracture networks at a range of scales, from the scale of a tunnel/cavern up to that of a site. Developing and testing these models has required large amounts of observational data on fracture properties, water inflows to boreholes and tunnels, hydraulic measurements, response to excavation and borehole drilling and pumping, and dedicated cross-hole interference tests. Understanding has reached a stage where quantitative flow criteria can be developed for acceptance of volumes of rock for disposal at all scales. For example data from pilot boreholes can be used to predict tunnel inflows in advance of excavation and to support detailed operational design decisions.

An illustration of the complexity of fractured rock masses and the impact they can have on hydrogeological assessments of post-closure safety of a GDF is provided by the example of the site investigations in the 1990s that supported the application for a licence to construct a rock characterization facility (RCF) in the Borrowdale Volcanic Group (BVG), west Cumbria (Chaplow, 1996).

Structural 'domains' defined by characteristic fracture density and orientation were shown to correlate broadly with rock properties (Barnes et al., 1998). As is typical of fractured rock masses, the fluid flow regime in the BVG is complex and heterogeneous. High head pressures beneath the low-lying Cumbrian coast led to conflicting interpretations, in one of which the proposed RCF would have been located in the path of westward groundwater flow between the high topography of the Lakeland fells and the Irish Sea. Conversely indications from pumping tests of low connectivity between the BVG and overlying Permian and Triassic aquifers suggest that the apparently high head pressures were 'locked in' from the last glacial maximum. In this model pore fluid overpressures (i.e. greater than hydrostatic) developed in poorly vertically connected stratigraphy when the area was affected by the lithostatic load imposed by a kilometre or more of ice (Black and Barker, 2016).

Whilst the 1990s site investigations in west Cumbria did not comprise a comprehensive characterization programme for a GDF they did illustrate a specific challenge in such environments: the development of representative models of larger rock volumes based on upscaling of fractures and flow characteristics measured from individual boreholes (Knipe, 1996). The current UK site selection programme will benefit from the considerable progress that has been made in refining methods for upscaling borehole data to produce discrete fracture network and continuous porous medium models of fractured oil and gas reservoirs (e.g. James, 2007).

11. Geological events and processes that contribute to containment and isolation

The International Features, Events and Processes (FEP) list (Capouet et al., 2019) aims to provide comprehensive treatment of all FEPs irrespective of geological setting. It includes several geological FEPs that will not be considered in detail here, given the UK's relatively quiescent tectonic setting. Specifically events and processes related to tectonics, orogeny, magmatic and volcanic activity, metamorphism, and regional erosion (as contrasting to local erosion related, for example, to glacial and periglacial processes) are not discussed further (Connor et al., 2009). Glacio-tectonics such as post-glacial faulting and associated seismicity is however a consideration discussed here under processes associated with continental glaciations.

The long-term post-closure evolution of a GDF will depend on many FEPs and their analysis is used to develop a range of scenarios that can be assessed as part of the post-closure modelling process. A base case scenario describes the expected evolution, with a range of variant scenarios representing possible deviations from the base scenario caused by FEPs that may or may not occur. For a given scenario there will exist data and model uncertainty therefore, and various strategies can be applied to deal with them. The GDF Programme will benefit from sophisticated methods that other industries have evolved to manage subsurface uncertainty, particularly oil and gas, and mining.

11.1. Continental glaciations

In England and Wales the most significant natural surface processes that could affect the performance of a GDF are those associated with continental glaciations. A considerable volume of research has been conducted to understand their potential impact on long-term GDF safety, particularly in Finland and Sweden. This section describes the main glacial processes that the GDF Programme will take into account.

Continental glaciations are likely to affect the UK over the next million years, even though they are considered unlikely in the most critical period for containment of the next 100,000 years. Taking account only of the well-understood astronomical forcing factors that affect insolation, a reduced-complexity process-based model for the long-term evolution of the global ice volume assigns high probability of glacial occurrence between 50,000 and 90,000 years after the present. However the superimposed high cumulative anthropogenic CO_2 emissions are now considered more likely to lead to northern hemisphere ice-free landmass conditions throughout the next half a million years, postponing glacial inception to 500,000 years after present (Ganopolski et al., 2016; Talento and Ganopolski, 2021). Conservative safety cases take such uncertainties into account using a range of possible scenarios of climate evolution (e.g. Posiva, 2021a,b). However the rapid decline in hazard potential of the wastes over the period in which glaciations seem unlikely to occur suggest that accounting for possible glacial impacts should not be a leading driver in GDF design and siting decisions.

The following glacial and periglacial processes could affect a GDF to inform the site selection process, concept design, construction, operation and closure.

11.2. Uplift and regional tilting

Land level changes due to glacio-isostatic adjustment (still ongoing at a rate that exceeds current sea level rise at the GDF sites in Finland and Sweden, following the Weichselian glaciation: Svensson, 1991) could impact a GDF in different ways and will need to be taken account of in safety cases. For example they could lead to local enhancement of rates of bedrock erosion, changes to groundwater chemistry (due to marine incursion and related saltwater intrusion), and perturbations of the ambient stress field.

Tilting occurs on wavelengths of at least tens of kilometres but is unlikely to lead to inclinations that would be sufficiently steep to have an impact on GDF integrity. However tilting can be significant in reconfiguring drainage basins and could impact long-term hydrology and groundwater flow. Proposed excavation of c.500km^3 sediment from the Lower Severn Valley during the last 50,000 years or so has been modelled to have led to a flexurally enhanced south-eastward tilt of the land surface in southern England (Watts et al., 2000). This caused the Thames watershed to shift some 100 km south-eastward, thereafter cutting off West Midlands Triassic and older rocks from the Thames drainage basin.

11.2.1. Rates of relative land-sea level change

Despite relatively high rates of present day glacio-isostatic uplift (up to 1.6 mm y^{-1} in central Scotland, −0.5 mm y^{-1} in south-east England: Shennan and Horton, 2002), following unloading the time taken for such uplift to decline to equilibrium has been modelled to vary between 40,000 years–75,000 years (SKB, 2010). The non-linear nature of solid Earth isostatic rebound mean that this range shows little variation between different scenarios – for example combinations of single and multiple glacial cycles – and does not vary much with different magnitudes of isostatic deformation (because regions of greatest deformation recover more rapidly).

11.2.2. Erosion

Ice streams and periglacial rivers can carve significant valleys, reshape upland topography and reconfigure sediment distribution systems. Photographs of receding glaciers in Iceland taken 20 years apart reveal freshly exposed cliffs at least 100 m high (e.g. Sólheimajökull: Eliasson, 2019). The famous Goring Gap in the Chiltern Hills, southern England formed due to accelerated headwater capture by periglacial streams that cut through a Chalk ridge some 450,000 years ago (Hey, 1996). Incision rates in these settings can far exceed those in areas of active tectonics – up to 160 m My^{-1} in the Thames valley through the Quaternary (Bridgland, 2010). To minimise the possibility that glacial and periglacial erosion could remove a large proportion of the overburden, a GDF in England and Wales will not be constructed at depths shallower than 200 m (Elsterian sub-glacial valleys are up to 600 m deep in the northern Netherlands: Verhoef et al., 2017).

11.2.3. Permafrost and perturbation of groundwater flow

The hydrogeology of glaciated regions near to ice margins is complex largely because of permafrost occurrence (Posiva, 2019a, 2019b). In northern Canada permafrost extends as deep as 500 m–700 m (Ruskeeniemi et al., 2004) and modelling of England and Wales indicates it could be up to c.250 m deep in cold conditions (Busby et al., 2015). Among the impacts that permafrost could have on GDF integrity, McEvoy et al. (2016) list performance of the engineered barrier (although clay-based buffers and backfills regain their properties after thawing), brine accumulation and migration, methane hydrate formation, and pore pressure changes associated with volume gain at the water-ice phase transition. Permafrost also creates a permeability barrier that can affect groundwater flow, recharge and discharge (see also Cohen-Corticchiato and Zwinger, 2021).

11.2.4. Groundwater chemistry in glacial environments

Glacial periods are associated with higher recharge, higher head pressure gradients and greater potential for pore fluid overpressures in subglacial substrates. This can cause penetration of fresh, oxidising meteoric water to greater depths than during interglacial periods, leading to rejuvenation of corrosion of canisters and other components of the engineered barrier with enhanced production of gases. Anaerobic corrosion of metals is expected to be the main mechanism by which hydrogen gas can be formed. If the gas generation rate is larger than the capacity for migration out of the system as a dissolved gas the pore water will become oversaturated and a free gas phase will form. The EBS will be designed to limit corrosion rates of iron and steel but there may be other metals present (e.g. carbon steel, stainless steel, aluminium) where corrosion rates could generate significant gas (Verhoef et al., 2017 op cit.).

Interaction of dilute groundwaters with bentonite could lead to erosion (SKB, 2009; SKB, 2017), the formation of bentonite colloids and some degradation of the bentonite barrier function including a reduction in density and degree of compaction (Wilson et al., 2011). Influxes of freshwater can also drive expansion and migration of wet rockhead areas in which salt-bearing formations can be disturbed by dissolution of halite intervals (Field et al., 2019; Hough et al., 2011). In the Cheshire Basin halite and mudstone generally become impermeable at relatively shallow depth, with fissures and fractures closed at a depth of about 180 m (Howell et al., 1984). In glacial times however it is likely that fresh groundwaters were forced to much greater depths of 300 m (Boulton et al., 1995; Cooper et al., 2002), or more (Heathcote and Michie, 2004).

11.2.5. Lithostatic loading

Ice thickness in southern Britain was up to 1200 m at the last glacial maximum 20,000 years ago (Tushingham and Peltier, 1991; Lambeck et al., 1998). Rock stresses will be affected by the ice load and the hydrostatic pressure. For a GDF at 650 m depth 1200 m ice would impose an additional 12 MPa vertical load, increasing lithostatic pressure by approximately 60% (assuming average rock overburden density of 3000 kg m^{-3}). Horizontal stress will also increase. If the ice sheet is warm-based (i.e. temperate glaciers in lower latitudes where the ice moves relatively rapidly) the prevailing water pressures at the ice-rock interface will influence rock stresses, and they will also be altered according to duration of the ice load and the slope of the ice surface (Posiva, 2019a, 2019b op cit.; Cohen-Corticchiato and Zwinger, 2021 op cit.). There are few published studies of the impact of cycles of ice loading-unloading on rock properties and GDF performance but they could include the following processes:

- reduction of porosity and matrix permeability;
- pore fluid overpressure and reduction of effective stress, promoting the formation and/or reactivation of fractures;
- initiation or enhancement of fractures and related microseismicity, particularly where fractures are steeply oriented;

- creation of head pressure gradients due to heterogeneous ice loading, driving lateral groundwater flow; and
- increased seismicity.

11.3. *Earthquakes and in situ stress*

The UK landmass is seismically quiet – there are no known seismically active faults that intersect the present land surface – but is not immune to earthquakes. Focal mechanisms from the most reliable fault data indicate the dominant mode of active faulting is strike-slip (Baptie, 2010) with most large events (≥4.5M_W) nucleating at depths >10 km (Musson and Sargeant, 2007).

Seismic shaking and the potential for seismically induced shear movements need to be taken into account in planning GDF operations and assessing post-closure integrity. As is required for other nuclear installations, a comprehensive seismic hazard assessment for both GDF surface facilities and underground structures will need to be undertaken for any potential site. This will entail probabilistic analysis of seismic hazard and a survey of local structures to understand their potential for reactivation. In other seismically quiet regions such as Sweden and Finland, GDF seismic hazard evaluation has focused on the potential for faulting associated with large magnitude post-glacial earthquakes (Steffen et al., 2022) to cause shear movements on existing fractures in the repository bedrock that might affect waste packages (Posiva, 2019a, 2019b).

Earthquakes are a manifestation of the accumulation and sudden release of elastic strain energy, controlled mainly by the in situ stress field and the orientations and properties of faults and fractures in the upper and middle crust. The UK's in situ stress field (Fig. 8) reflects a range of competing stress-generating mechanisms (Firth and Stewart, 2000), swinging counter-clockwise from a NNW-SSE trend in southern Britain where post-Alpine stress dominates, to NW-SE further north

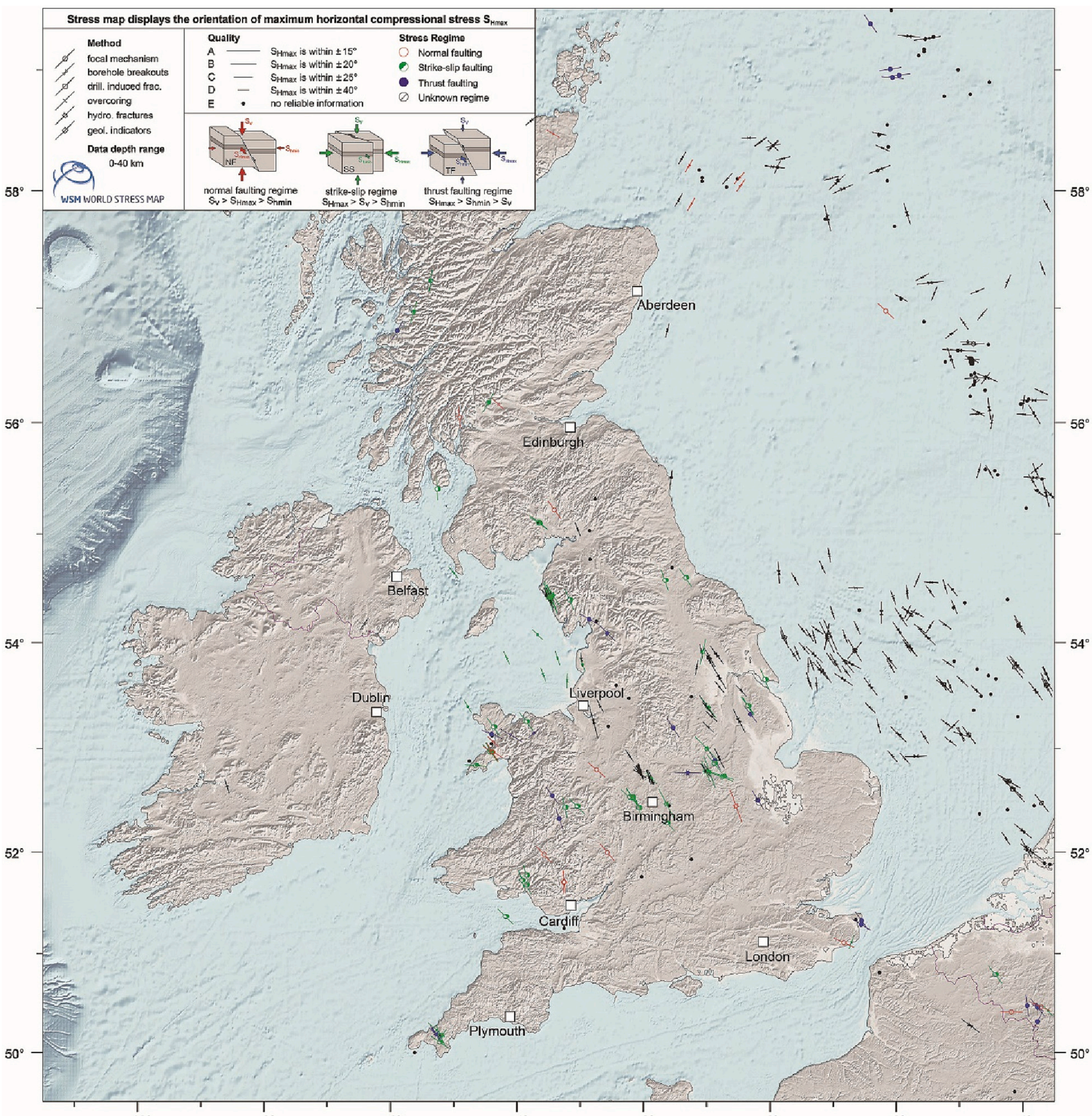

Fig. 8. UK in situ maximum horizontal stress azimuths. Kingdon et al., 2022.

nearer the influence of mid-Atlantic ridge-push. The in situ stress field in a GDF host rock impacts the design, orientation and support systems of the openings constructed for access and waste emplacement, especially if there is marked anisotropy in horizontal stress components. The stress field also affects the stability of the rock mass during excavation and the stability and response of fracture zones to natural and repository-induced stresses, including the nature of excavation damage zones associated with stress concentrations around shafts, tunnels and vaults (see next *sec*tion).

Seismicity could disrupt the engineered barrier system components of a GDF, the surrounding rocks and the ground surface in the following ways:

- earthquake-associated shaking could disturb a GDF including the surface facilities during its operational lifetime, although the intensity of shaking and the likelihood of disturbances to a GDF diminish significantly with depth (Fukushima et al., 1995; Abercrombie, 1997);
- surface effects could include soil liquefaction, collapse of structures, and landslips;
- seismic pumping of fluids along faults (fault valve behaviour: Sibson, 1990) perturbs pressure gradients leading to movement of large fluid volumes; and
- changes in fluid chemistry have been related directly to local seismicity (e.g. pH: Stillings et al., 2021).

Fault rupture hazard will also be an important consideration in siting and designing a GDF. No UK regulatory guidance yet exists but the Swedish waste management organisation specifies that the copper canister in which spent fuel will be packaged should remain intact after a 5 cm shear displacement at 1 m sec^{-1}. Secondary rock shear of such magnitude in the fracture network around waste containers would require large magnitude slips on nearby earthquake-generating faults (e.g. studies in Finland suggest earthquakes of $M_W > 7$ would be required on major faults at distances of only some hundreds of metres from the GDF). Since faults capable of hosting large earthquakes would be avoided in siting a GDF, this scenario is unlikely.

In the UK, the faults that host recorded earthquakes have themselves slipped only small amounts, so the potential for secondary shear in rock some distance away is small. For example the 1931 Dogger Bank event, at 6.1M_W the largest UK earthquake in living memory, was sourced on a fault that slipped c.20 cm at a depth of 20 km (based on seismic moment

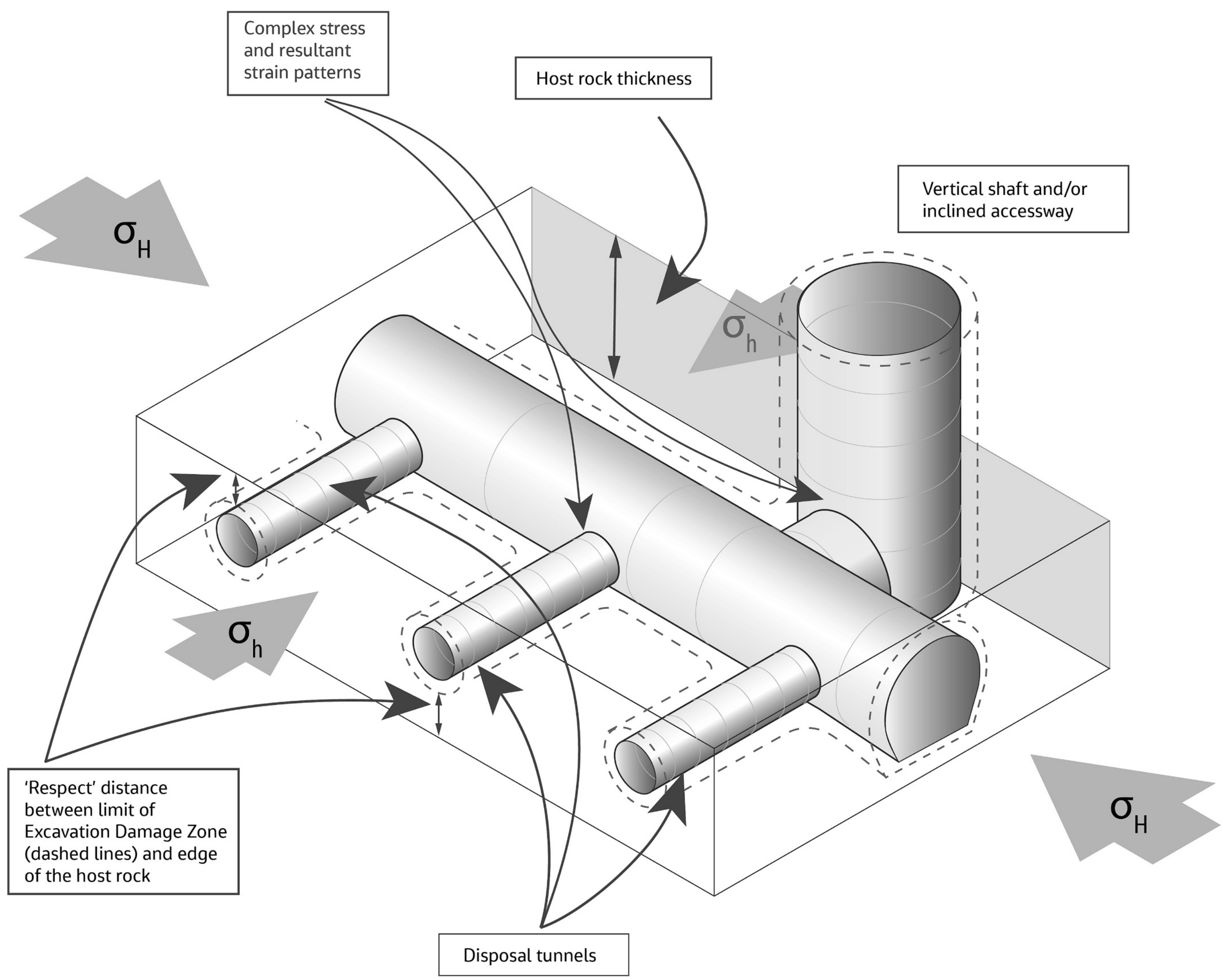

Fig. 9. Schematic perspective view of shafts and tunnels and their associated excavation damage zones (EDZ). The nature of EDZs depends on the scale and geometry of an excavation, rock properties, and the orientation of excavations with respect to the azimuth and magnitudes of the principal in situ stresses (σ_H = maximum horizontal principal stress, $\sigma_{h\cdot}$ = minimum horizontal principal stress).

vs. source radius data in Hanks, 1977). The UK's largest coal mining-induced event at 3.1M_W resulted from c.8 mm slip at 600 m depth, and typical fraccing-induced tremors are Richter magnitude $-1.0M_W$, sourced on near-surface faults slipping c.0.1 mm.

Given the seismically benign nature of the UK, with no major disruptive earthquakes, seismic risks are not considered high, but will be taken into consideration for GDF site selection and design.

11.4. Induced rock damage

The impact of human-induced rock deformation, or excavation damage, needs to be understood throughout GDF design and construction in order to mitigate any operational risks that it could pose, and so that it may be incorporated in models of the initial state of the multi-barrier system at the point of closure of a GDF (Follin et al., 2021). Subsurface excavation can create excavation damage zones (EDZ) whose nature and magnitude depends on the in situ stress field, rock properties, orientation and geometry of the structure, and the excavation technology used (blasting, tunnel boring, road-header, etc).

Heat from the wastes can also impact strain in the rock formations above a GDF. One-dimensional models have been used to examine the amount of uplift that could result from emplacing HHGW in a GDF up to 650 m deep (Holton et al., 2020; Tsang et al., 2012). Depending on host rock type they indicate 30 cm–115 cm uplift occurring over a period of 5000 years–15,000 years, although these modest amounts are likely to be maxima because they do not incorporate the effects of lateral heat dissipation.

EDZs may comprise both radial and concentric fractures, with more complex geometries at the intersections of tunnels and shafts (Fig. 9). The dimensions and geometry of an EDZ will depend on relations between rock strength and the perturbed stress magnitude and azimuth but most EDZs extend between a few centimetres and a few metres into the rock (Arcos et al., 2005). The width of the respect zone between the margin of an EDZ and the top and base of a GDF host rock unit also exerts a constraint on the minimum host rock thickness in which a GDF could be constructed.

Excavation damage can have implications for a GDF safety case that include:

- increased fracture permeability and the creation of connected pathways in the near-field environment;
- spalling and rockfalls during the excavation and operational period before tunnels are backfilled;
- desaturation and/or local changes to groundwater transport pathways;
- changes in host rock redox conditions; and
- formation of new fractures, reactivation of existing fractures and associated microseismicity.

In mines and underground rock laboratories excavation damage is often expressed as open-aperture fractures intersecting the walls, floors and ceilings of tunnels, with more complex fracture geometries at tunnel and shaft junctions. In rock types that exhibit more plastic rheologies under the confining pressures encountered at several hundred metres depth, fractures in some EDZs may 'self-heal'. Tunnels excavated in rock salt and other visco-plastic lithologies can exhibit pronounced bulging of ceilings, walls and floors due to creep. If a GDF were to be constructed in these types of host rock it will be important to establish the extent to which excavation damage self-heals, and the duration of the healing process (Tsang et al., 2005). Detailed understanding of the nature of fracture self-healing is the focus of ongoing international research.

12. Discussion and summary

The GDF Programme will result in the implementation of a major and essential item of national infrastructure required to secure the UK's future energy security as an integral part of the whole-lifecycle management of the next generation of nuclear reactors. It will also remove the enduring cost, environmental and security burden of the legacy nuclear waste inventory.

In common with most other countries evaluating options for permanent disposal of higher activity nuclear waste, England and Wales have chosen deep geological disposal as the most appropriate solution currently available – one that will provide a high level of safety at all times into the far future. Development consent to construct a GDF will require a willing and involved host community, appropriately packaged waste, and a suitable site.

NWS, the organisation tasked with developing a GDF in England and Wales, is currently engaged with four Community Partnerships: two in Copeland, southwest Cumbria, one in Allerdale, northwest Cumbria, and one on the English east coast in Theddlethorpe, Lincolnshire. In all of these Community Partnerships Mesozoic Lower Strength Sedimentary Rocks have been identified as potential GDF host rocks and are being investigated further. A dedicated 3D seismic survey was acquired off the coast of Copeland in 2022.

This paper has described the main geological features, events and processes (FEPs) relevant to the situation and environment of England and Wales that will need to be considered to demonstrate that a site is suitable for a GDF. We have grouped them into host rock type material properties, the nature of deformational structures, groundwater characteristics and behaviour, and natural processes such as glaciations and earthquakes. All of them are potentially relevant to GDF siting decisions. Whether each of the FEPs described here become important for future siting decisions will depend on the location of individual sites and their particular characteristics, including the geological setting.

The containment function of a GDF is delivered by a combination of rock and engineered barriers working together – the multibarrier system. Only when the specifics of geology at a subsurface site are better known can the engineered barriers be optimized to deliver the best possible long-term isolation and containment solution. Many combinations of site properties and engineered barrier design can provide the high levels of containment and isolation required by regulators. The site for a GDF in England and Wales will be decided on the basis of a wide range of factors such as the degree of local commitment, environmental impacts, cost and waste transport options, once sufficient work has been carried out to ensure that a site and linked GDF design will meet safety requirements and standards.

This paper has not focused on past and future exploitation of natural resources as a criterion for selecting suitable GDF sites. However a GDF and the subsurface volume it occupies is a national resource in itself. With competing and sometimes conflicting demands on the subsurface a subsurface strategy, a national system of records and land control, may be needed. The International Atomic Energy Agency (2011) safety guidance and requirements, and the Guidance on Requirements for Authorisation (Environment Agency and Northern Ireland Environment Agency, 2009op. cit.) state that a GDF should be sited away from known areas of underground resources because these are places where the likelihood of human disturbance of a facility in the future is greater. Areas that have been intensively exploited for resources also need to be taken account of in a GDF siting process because mining has resulted in an often poorly surveyed network of shafts and tunnels that could disturb the groundwater system, provide pathways for radionuclide migration to the surface, and present drilling hazards.

Whilst there are examples of areas in England and Wales that would be avoided due to historical exploitation of resources, there are not enough data to define them precisely and doing so would be an objective of site characterization. Moreover it is not possible to define what might constitute a resource in the future. However some specific areas that are currently licensed for exploration and/or exploitation of resources (mainly Coal Mining Licences and Petroleum Exploration and Development Licences) and carbon storage licensing rounds would need to be monitored throughout the GDF Programme.

Safety cases are fundamental to the GDF siting process: a GDF will not be constructed unless NWS, the independent regulators and the host community are satisfied that it can be operated safely and that radionuclides can be isolated and contained for hundreds of thousands of years. Safety cases are structured according to claims and detailed arguments informed by evidence. In each region being investigated for its potential to host a GDF, the subsurface will be characterized using data mainly from seismic reflection and deep investigation boreholes to assemble the site-specific evidence needed to produce robust safety cases.

Understanding of how deep geology at potential GDF sites could contribute to their long-term safety will increase progressively with successive tranches of dedicated data acquisition and new analysis and modelling. Multiple iterations of site descriptive models, representing the aggregated knowledge of the subsurface at a specific site, will be used to track changes in key uncertainties and thereby assess further information requirements for safety cases and engineering and design. Uncertainty is an inherent feature of subsurface characterization because of the incomplete understanding of rock properties and fluids that it yields. Site descriptive models will be a powerful tool with which to convey the evolving understanding of the subsurface geology to a broad range of stakeholders.

Strong progress is also being made by overseas waste management organisations.

- The Finnish Government granted Posiva a licence in 2015 to construct the Onkalo final disposal facility for spent nuclear fuel in Archaean gneissic rocks at Olkiluoto on the Baltic coast. Posiva is presently conducting full-scale in situ system tests in underground tunnels using dummy fuel canisters. The disposal facility and encapsulation plant are under construction with a large part of the central section already completed. It is anticipated that the GDF will become operational in the next few years once the current operational licence review stage is completed.
- In Sweden SKB received approval from the government in 2022 to construct its final repository for spent nuclear fuel in Archaean granitoids at Forsmark on the Baltic coast, with the encapsulation plant to be built at Oskarshamn. SKB plans to start work on construction of its GDF in 2023 commencing operations some ten years later.
- Nagra, the Swiss waste management organisation, has used seismic reflection data and deep boreholes to evaluate three sites in the northern Alpine basin, all focused on the Middle Jurassic Opalinus claystone as host rock. In September 2022 they selected the Nördlich Lägern site to proceed to submission of a licence application to the government in 2024. Emplacement of low- and intermediate-level waste is expected to start around 2050, with high-level waste emplacement following some ten years later.
- Cigéo, the French deep geological disposal project for high- and intermediate-level long-lived radioactive waste, received formal recognition in July 2022 of the general interest of the project in protecting people and the environment in the very long term. A repository will be constructed in a Middle Jurassic claystone at 500 m depth beneath the eastern Paris basin, following some 20 years of investigations at the same site. In January 2023 ANDRA, the organisation tasked with delivering the deep geological disposal project, submitted a licence to construct a facility in the vicinity of the underground rock laboratory. Reversibility is a key principle of the Cigéo project, ensuring that future generations are able to regularly reassess decisions made in the past and continue building and operating successive deep disposal facilities.
- The Nuclear Waste Management Organisation of Canada initiated a site selection process in 2010 with site selection and approvals anticipated to take many years to complete. Used fuel transportation, handling and emplacement operations in a repository will occur over a period of about 40 years followed by an extended period of monitoring, decommissioning, closure and post-closure monitoring.

The UK's GDF Programme benefits greatly from collaboration with these and other waste management organisations through joint experiments in underground rock laboratories, site visits and knowledge transfer workshops. International collaborations will continue to be a central feature of nuclear disposal programmes worldwide as the global community confronts the challenge of safely disposing of its higher activity wastes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Abercrombie, R.E., 1997. Near-surface attenuation and site effects from comparison of surface and deep borehole recordings. Bull. Seismol. Soc. Am. 87 (3), 731–744.
Arcos, D.A., Hernan, P., Cruz, B., Herbert, H.J., Savage, D., Smart, N.R., Villar, M.V., Van Loon, L.R., 2005. NF-PRO: Understanding and Physical and Numerical Modelling of the Key Processes in the Near-field and their Coupling for Different Host Rocks and Repository Strategies, EDZ Development and Evolution, RTDC-2 Synthesis Report. EC integrated project NF-PRO Deliverable D-No:2.6.4.
Armand, G., Conil, N., Talandier, J., Seyedi, D.M., 2017. Fundamental aspects of the hydromechanical behaviour of Callovo-Oxfordian claystone: from experimental studies to model calibration and validation. Comput. Geotech. 85, 277–286.
Armand, G., Noiret, A., Zghondi, J., Seyedi, D.M., 2013. Short-and long-term behaviors of drifts in the Callovo-Oxfordian claystone at the Meuse/Haute-Marne Underground Research Laboratory. J. Rock Mech. Geotech. Eng. 5 (3), 221–230.
Armitage, P.J., Worden, R.H., Faulkner, D.R., Butcher, A.R., Espie, A.A., 2016. Permeability of the Mercia Mudstone: suitability as caprock to carbon capture and storage sites. Geofluids 16 (1), 26–42.
Baptie, B., 2010. Seismogenesis and state of stress in the UK. Tectonophysics 482 (1–4), 150–159.
Barnes, R.P., Dee, S.J., Sanderson, D.J., Bowden, R.A., 1998. Interpretation of structural domains in discontinuity data from Nirex deep boreholes at Sellafield. Proc. Yorks. Geol. Soc. 52 (2), 177–187.
Black, J.H., Barker, J.A., 2016. The puzzle of high heads beneath the West Cumbrian coast, UK: a possible solution. Hydrogeol. J. 24 (2), 439–457.
Boisson, J.Y., 2005. Working Group on the Characterization, the Understanding and the Performance of Argillaceous Rocks as Repository Host Formations. In: Clay Club Catalogue of Characteristics of Argillaceous Rocks. OECD Publications.
Bossart, P., Thury, M., 2011. Characteristics of the Opalinus Clay at Mont Terri. Mont Terri Project, Wabern Switzerland.
Bossart, P., Bernier, F., Birkholzer, J., Bruggeman, C., Connolly, P., Dewonck, S., Fukaya, M., Herfort, M., Jensen, M., Matray, J.M., Mayor, J.C., 2018. Mont Terri rock laboratory, 20 years of research: introduction, site characteristics and overview of experiments. In: Mont Terri Rock Laboratory, 20 Years, pp. 3–22.
Boulton, G.S., Caban, P.E., Van Gijssel, K., 1995. Groundwater flow beneath ice sheets: Part I—Large scale patterns. Quat. Sci. Rev. 14 (6), 545–562.
Branney, M.J., Kokelaar, P., 1994. Volcanotectonic faulting, soft-state deformation, and rheomorphism of tuffs during development of a piecemeal caldera, English Lake District. Geol. Soc. Am. Bull. 106 (4), 507–530.
Branney, M.J., Soper, N.J., 1988. Ordovician volcano-tectonics in the English Lake District. J. Geol. Soc. 145 (3), 367–376.
Bridgland, D.R., 2010. The record from British Quaternary river systems within the context of global fluvial archives. J. Quat. Sci. 25 (4), 433–446.
British Geological Survey, 2020. The BGS Lexicon of Named Rock Units [Online]. Available from:

Busby, J.P., Lee, J.R., Kender, S., Williamson, J.P., Norris, S., 2015. Modelling the potential for permafrost development on a radioactive waste geological disposal facility in Great Britain. Proc. Geol. Assoc. 126 (6), 664–674.
Butler, M., Jamieson, R., 2013. Preliminary Interpretation of Six Regional Seismic Profiles across Onshore Basins of England. UK Onshore Geophysical Library, London.
Capouet, M., Carter, A., Ciambrella, M., 2019. International Features, Events and Processes (IFEP) List for the Deep Geological Disposal of Radioactive Waste. Version 3.0 (No. NEA-RWM-R–2019-1). Organisation for Economic Co-Operation and Development.
Chaplow, R., 1996. The geology and hydrogeology of Sellafield: an overview. Q. J. Eng. Geol. Hydrogeol. 29 (Supplement 1), S1–S12.
Chapman, N.A., McCombie, C.M., 2003. Principles and Standards for the Disposal of Long-Lived Radioactive Wastes. In: Waste Management Series, Vol 3. Elsevier (Pergamon)., Amsterdam.
Chapman, N.A., Hooper, A., 2012. The Disposal of Radioactive Wastes Underground. Proc. Geol. Assoc. 123 (1), 46–63.
Chen, J., Ren, S., Yang, C., Jiang, D., Li, L., 2013. Self-healing characteristics of damaged rock salt under different healing conditions. Materials 6 (8), 3438–3450.
Cohen-Corticchiato, D., Zwinger, T., 2021. Modeling Permafrost Evolution at Olkiluoto for the Next 120,000 Years. Posiva Oy, Eurajoki, Finland. Working Report 2021–14.
Connor, C.B., Chapman, N.A., Connor, L.J. (Eds.), 2009. Volcanic and Tectonic Hazard Assessment for Nuclear Facilities. Cambridge University Press, Cambridge.
Cooper, R.J., Wadham, J.L., Tranter, M., Hodgkins, R., Peters, N.E., 2002. Groundwater hydrochemistry in the active layer of the proglacial zone, Finsterwalderbreen, Svalbard. J. Hydrol. 269 (3–4), 208–223.
Diaconu, D., Detilleux, V., Strusińska-Correia, A., Göbel, A., Dewoghelaere, J., Becker, D. A., 2023. UMAN–a pluralistic view of uncertainty management. EPJ Nucl. Sci. Technol. 9, 2.
Edmunds, W.M., Smedley, P.L., 2000. Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. Appl. Geochem. 15 (6), 737–752.
Eliasson, O., 2019. The glacier melt series 1999/2019. Available from: https://www.glaciermelt.is.
Environment Agency and Northern Ireland Environment Agency, 2009. Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation.
European Commission, 2011. Council Directive 2011/70/EURATOM, Establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. Available from: https://www.legislation.gov.uk/eudr/2011/70.
Ferry, S., Pellenard, P., Collin, P.Y., Thierry, J., Marchand, D., Deconinck, J.F., Robin, C., Carpentier, C., Durlet, C., Curial, A., 2007. Synthesis of recent stratigraphic data on Bathonian to Oxfordian deposits of the eastern Paris Basin. Mém. Soc. Géol. France 178 (3).
Field, L.P., Milodowski, A.E., Evans, D., Palumbo-Roe, B., Hall, M.R., Marriott, A.L., Barlow, T., Devez, A., 2019. Determining constraints imposed by salt fabrics on the morphology of solution-mined energy storage cavities, through dissolution experiments using brine and seawater in halite. Q. J. Eng. Geol. Hydrogeol. 52 (2), 240–254.
Firth, C.R., Stewart, I.S., 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift Centre. Quat. Sci. Rev. 19 (14–15), 1469–1493.
Flynn, J.H., Slovic, P., Kunreuther, H., 2001. Risk, Media and Stigma: Understanding Public Challenges to Modern Science and Technology. Earthscan.
Follin, S., Koskinen, L., Suikkanen, J., Riihiluoma, N., Kantia, P., Kiuru, R., Mustonen, S., 2021. Characterization of EDZ for Final Disposal Facility of Spent Nuclear Fuel in Olkiluoto. Posiva Report 2021-16.
Fukushima, Y., Gariel, J.C., Tanaka, R., 1995. Site-dependent attenuation relations of seismic motion parameters at depth using borehole data. Bull. Seismol. Soc. Am. 85 (6), 1790–1804.
Ganopolski, A., Winkelmann, R., Schellnhuber, H.J., 2016. Critical insolation–CO2 relation for diagnosing past and future glacial inception. Nature 529 (7585), 200–203.
Gautschi, A., 2017. Safety-relevant hydrogeological properties of the claystone barrier of a swiss radioactive waste repository: an evaluation using multiple lines of evidence. Grundwasser 22 (3), 221–233. https://doi.org/10.1007/s00767-017-0364-1.
Gluyas, J.G., Swarbrick, R.E., 2021. Petroleum geoscience. John Wiley & Sons.
Gutiérrez-Rodrigo, V., Villar, M.V., Martín, P.L., Romero, F.J., Barcala, J.M., 2015. Gas-breakthrough pressure of FEBEX bentonite. Geol. Soc. Lond., Spec. Publ. 415 (1), 47–57. DSSC/455/01 121 104.
Hancock, P.L., 1985. Brittle microtectonics: principles and practice. J. Struct. Geol. 7 (3–4), 437–457.
Hanks, T.C., 1977. Earthquake stress drops, ambient tectonic stresses and stresses that drive plate motions. In: Stress in the Earth. Birkhäuser, Basel, pp. 441–458.
Haynes, H.M., Bailey, M.T., Lloyd, J.R., 2021. Bentonite barrier materials and the control of microbial processes: Safety case implications for the geological disposal of radioactive waste. Chem. Geol. 581, 120353.
Heathcote, J.A., Michie, U.McL., 2004. Estimating hydrogeological conditions overthe last 120 ka: an example from the Sellafield area, UK. J. Geol. Soc. Lond. 161, 995–1008.
Hey, R.W., 1996. The origin and early history of the upper Thames. Quat. Sci. Rev. 15 (5–6), 407–411.
Hillis, R.R., Holford, S.P., Green, P.F., Doré, A.G., Gatliff, R.W., Stoker, M.S., Thomson, K., Turner, J.P., Underhill, J.R., Williams, G.A., 2008. Cenozoic exhumation of the southern British Isles. Geology 36 (5), 371–374.
Hobbs, P., Hallam, J.R., Forster, A., Entwisle, D., Jones, L.D., Cripps, A.C., Northmore, K. J., Self, S., Meakin, J.L., 2002. Engineering geology of British rocks and soils: Mudstones of the Mercia Mudstone Group. British Geological Survey.
Hoch, A.R., Baston, G.M.N., Glasser, F.P., Hunter, F.M.I., Smith, V., 2012. Modelling evolution in the near field of a cementitious repository. Mineral. Mag. 76 (8), 3055–3069.
Holton, D., Roberts, D., Williams, T., 2020. Investigating the Thermo-Hydro-Mechanical Evolution of a UK Geological Disposal Facility Due to Disposal of High-Heat-Generating Wastes NDA Report no. RWM/Contr/20/006. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1128278/GDF_Bibliography_Summary_2007_to_2021.pdf.
Horseman, S.T., Hobbs, P., McEwen, T.J., Avery, L., Forster, A., 1982. Basic Geotechnical Properties of Core from the Harwell Boreholes. Brit. Geol. Surv. Rep. ENPU 82–87.
Hough, E., Evans, D.J., Williamson, J.P., 2011. A geological reappraisal of the Preesall Saltfield, Lancashire, United Kingdom: recognizing geological factors relevant to gas storage. In: Solution Mining Research Institute Fall Conference, 3–4 October 2011, York.
Howell, F. T., Castany, G., Groba, E., Romijn, E., n.d. Salt karst of the Cheshire Basin, England Hydrogeology of karstic terranes 1984 1 International Association Hydrogeologists. International Contributions to Hydrogeology 252–254.
Humphreys, Paul, West, J.M., Metcalfe, R., 2010. Microbial Effects on Repository IAEA, 2020. Design Principles and Approaches for Radioactive Waste Repositories. No. NW-T-1.27. Available from:. In: IAEA nuclear energy series. International Atomic Energy Agency, Vienna http://eprints.hud.ac.uk/id/eprint/7613/.
International Atomic Energy Agency, 2011. Disposal of radioactive waste, IAEA safety standards series no. SSR-5. SSN 1020–525, ISBN 978–92–0–103010–8, STI/PUB/1449.
James, D., 2007. In: Lonergan, L., Jolly, R.J.H., Rawnsley, K., Sanderson, D.J. (Eds.), Fractured Reservoirs, Geological Society Special Publication no. 270. Geological Society of London, London, Bath viii+ 285 pp.
Kim, Y.S., Sanderson, D.J., 2005. The relationship between displacement and length of faults: a review. Earth Sci. Rev. 68 (3–4), 317–334.
Kingdon, A., Williams, J., Fellgett, M., Heidbach, O., 2022. Stress Map of Great Britain and Ireland, GFZ Data Services. https://doi.org/10.5880/WSM.GreatBritainIreland2022. Available from:
Knipe, C.V., 1996. Appendix 1 to Inspector's Report. In: McDonald, C.S. (Ed.), Report on the Public Enquiry Appeal by United Kingdom Nirex Limited, Ref APP/ H0900/A/94/247019.
Kurosawa, S., Yui, M., Yoshikawa, H., 1996. Experimental study of colloid filtration by compacted bentonite. MRS Online Proc. Libr. (OPL) 465. https://doi.org/10.1557/PROC-465-963.
Lambeck, K., Smither, C., Johnston, P., 1998. Sea-level change, glacial rebound and mantle viscosity for northern Europe. Geophys. J. Int. 134 (1), 102–144.
Lee, J.O., Lim, J.G., Kang, I.M., Kwon, S., 2012. Swelling pressures of compacted Ca-bentonite. Eng. Geol. 129, 20–26.
McEvoy, F.M., Schofield, D.I., Shaw, R.P., Norris, S., 2016. Tectonic and climatic considerations for deep geological disposal of radioactive waste: a UK perspective. Sci. Total Environ. 571, 507–521.
Meleshyn, A., 2014. Microbial processes relevant for the long-term performance of high-level radioactive waste repositories in clays. Geol. Soc. Lond., Spec. Publ. 400 (1), 179–194.
Menaceur, H., Delage, P., Tang, A.M., Conil, N., 2015. The thermo-mechanical behaviour of the Callovo-Oxfordian claystone. Int. J. Rock Mech. Min. Sci. 78, 290–303.
Miller, W.M., Alexander, W.R., Chapman, N.A., McKinley, I.G., Smellie, J.A.T., 2001. In: Geological Disposal of Radioactive Wastes and Natural Analogues. Pergamon Press, Oxford. p, p. 316.
Musson, R.M.W., Sargeant, S.L., 2007. Eurocode 8 seismic hazard zoning maps for the UK. Brit. Geol. Surv. Tech. Rep. CR/07/125N, 70.
Nagra, 2019. Preliminary horizon and structure mapping of the Nagra 3D seismics JO-15 (Jura Ost) in time domain, Arbeitsbericht NAB 18-34.
Nagra, 2019. Preliminary horizon and structure mapping of the Nagra 3D seismics NL-16 (Nördlich Lägern) in time domain, Arbeitsbericht NAB 18-35.
Nagra, 2019. Preliminary horizon and structure mapping of the Nagra 3D seismics ZNO-97/16 (Zürich Nordost) in time domain, Arbeitsbericht NAB 18-36. Available from:.
NEA, 2022. In: OECD Clay Club Catalogue of Characteristics of Argillaceous Rocks, p. 176.
Norry, M.J., Dunham, A.C., Hudson, J.D., 1994. Mineralogy and geochemistry of the Peterborough Member, Oxford Clay Formation, Jurassic, UK: element fractionation during mudrock sedimentation. J. Geol. Soc. 151 (1), 195–207.
OECD., 2009. Considering Timescales in the Post-Closure Safety of Geological Disposal of Radioactive Waste. OECD Publishing, Paris, Radioactive Waste Management.
Ollila, K., 2013. Copper corrosion experiments under anoxic conditions, Kaija Ollila. VTT Technical Research Centre of Finland. ISSN 1402-3091, SKB R-13-34, ID 1393420.
Pei, Y., Paton, D.A., Knipe, R.J., Wu, K., 2015. A review of fault sealing behaviour and its evaluation in siliciclastic rocks. Earth Sci. Rev. 150, 121–138.
Pierpoint, N.D., 1996. The prediction and back analysis of excavation behaviour in Oxford Clay. University of Sheffield) (Doctoral dissertation.
Popp, T., Minkley, W., 2007. November. Integrity of a salt barrier during gas pressure build-up in a radioactive waste repository–Implications from laboratory investigations and field studies. In: Radioactive Waste Disposal in Geological Formations, Proceedings of the Conference RepoSafe 2007, Braunschweig, Germany, 6–9 November 2007.
Posiva, 2019. Co-Seismic Secondary Fracture Displacements Under Different Stress Conditions.
Posiva, 2019. Greenland ICE Project Final Report. Posiva Report 2019-19.
Posiva, 2021a. Safety Case for the Operating License Application: Selecting Climate Evolution Lines. Posiva Report 2021-09.
Posiva, 2021b. Rock Mechanics of Olkiluoto and 2021-15 Hydrogeology of Olkiluoto. Posiva Report 2021-18.

Rosborg, B., 2013. Post-test examination of a copper electrode from deposition hole 5 in the Prototype Repository, Rosborg Consulting. ISSN 1402-3091, SKB R-13-14, ID 1372781.
Ruskeeniemi, T., Ahonen, L., Paananen, M., Frape, S., Stotler, R.L., Hobbs, M., Kaija, J., Degnan, P., Blomqvist, R., Jensen, M.R., Lehto, J., Moren, M.R., Puigdomenech, I., Snellman, M., 2004. Permafrost at Lupin: Report of phase 2 (Geological Survey of Finland).
RWM, 2016. National Geological Screening - Detailed Technical Instructions and Protocols. Technical Note no. 24600903. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1128278/GDF_Bibliography_Summary_2007_to_2021.pdf. Available from:
RWM, 2021. Inventory for Geological Disposal, Main Report, DSSC/403/03. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1128278/GDF_Bibliography_Summary_2007_to_2021.pdf.
Shennan, I., Horton, B., 2002. Holocene land-and sea-level changes in Great Britain. J. Quat. Sci. 17 (5–6), 511–526.
Sibson, R.H., 1990. Conditions for fault-valve behaviour. Geol. Soc. Lond., Spec. Publ. 54 (1), 15–28.
Sibson, R.H., 2017. The edge of failure: critical stress overpressure states in different. Tectonic regimes. Geol. Soc. Lond., Spec. Publ. 458 (1), 131–141.
Sjöberg, L., Moen, B.E., Rundmo, T., 2004. Explaining risk perception. An evaluation of the psychometric paradigm in risk perception. research 10 (2), 612–665.
SKB, 1983. Final Storage of Spent Nuclear Fuel – KBS-3. Summary, Swedish Nuclear Fuel Supply Co.
SKB, 1999. Deep repository for spent nuclear fuel. SR 97 – Post-closure safety. Swedish Nuclear Fuel Supply Co.. Technical Report 99–28.
SKB, 2009. Bentonite erosion – Final Report. Swedish Nuclear Fuel Supply Co.. Technical Report 09–34.
SKB, 2010. Climate and climate-related issues for the safety assessment SR-PSU. Swedish Nuclear Fuel Supply Co.. Technical Report 10–49.
SKB, 2017. Revisiting bentonite erosion understanding and modelling based on the BELBaR project findings. Swedish Nuclear Fuel Supply Co.. Technical Report 17–12.
Smellie, J., Karlsson, F., 1996. A Reappraisal of some Cigar Lake Issues of Importance to Performance Assessment (SKB-TR–96-08). Sweden.
Steffen, H., Olesen, O., Sutinen, R., 2022. In: Glacially-Triggered Faulting. CUP, p. 438.
Stewart, I.S., Lewis, D., 2017. Communicating contested geoscience to the public: moving from 'matters of fact' to 'matters of concern'. Earth Sci. Rev. 174, 122–133.
Stillings, M., Lunn, R.J., Pytharouli, S., Shipton, Z.K., Kinali, M., Lord, R., Thompson, S., 2021. Microseismic events cause significant pH drops in groundwater. Geophys. Res. Lett. 48 (2), e2020GL089885.
Sundberg, J., 2017. Thermal properties and experiment at Äspö HRL. In: Rock Mechanics and Engineering, Volume 2. CRC Press, pp. 511–542.
Svensson, N.O., 1991. Postglacial land uplift patterns of South Sweden and the Baltic Sea region. Terra Nova 3 (4), 369–378.
Talento, S., Ganopolski, A., 2021. Reduced-complexity model for the impact of anthropogenic CO 2 emissions on future glacial cycles. Earth Syst. Dyn. 12 (4), 1275–1293.
Towler, G., Bond, A., 2011. Investigation of Gas Generation and Resaturation Issues: Input to EC FORGE Project.
Trouiller, A., 2006. Le Callovo-Oxfordien du bassin de Paris: du contexte géologique à la modélisation de ses propriétés. Compt. Rend. Géosci. 338 (12–13), 815–941.
Tsang, C.F., Barnichon, J.D., Birkholzer, J., Li, X.L., Liu, H.H., Sillen, X., 2012. Coupled thermo-hydro-mechanical processes in the near field of a high-level radioactive waste repository in clay formations. Int. J. Rock Mech. Min. Sci. 49, 31–44.
Tsang, C.F., Bernier, F., Davies, C., 2005. Geohydromechanical processes in the Excavation Damaged Zone in crystalline rock, rock salt, and indurated and plastic clays—in the context of radioactive waste disposal. Int. J. Rock Mech. Min. Sci. 42 (1), 109–125.
Tushingham, A., Peltier, W.R., 1991. Ice-3G: a new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change. J. Geophys. Res. Solid Earth 96 (B3), 4497–4523.
Urai, J.L., Spiers, C.J., 2017. The effect of grain boundary water on deformation mechanisms and rheology of rock salt during long-term deformation. In: The Mechanical Behavior of Salt–Understanding of THMC Processes in Salt. CRC Press, pp. 149–158.
Verhoef, E., Neeft, E., Chapman, N., McCombie, C., 2017. OPERA Safety Case. Available from: https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwir2taLzrf5AhXLh1wKHd8qDHUQFnoECBAQAQ&url=https%3A%2F%2Fwww.covra.nl%2Fapp%2Fuploads%2F2019%2F08%2FOpera-SafetyCase-samenvatting.pdf&usg=AOvVaw1ziouV24Cc4Ln1UpBes-km.
Watson, C., Savage, D., Wilson, J., 2011. Long-Term Cement Studies: Maqarin Natural Analogue. Quintessa Report to RWM, QRS-1523B-1, Version 2.0. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1128278/GDF_Bibliography_Summary_2007_to_2021.pdf.
Watts, A.B., McKerrow, W.S., Fielding, E., 2000. Lithospheric flexure, uplift, and landscape evolution in south-Central England. J. Geol. Soc. 157 (6), 1169–1177.
West, J.M., McKinley, I.G., 2002. The geomicrobiology of radioactive waste disposal. In: Bitton, G. (Ed.), The Encyclopaedia of Environmental Microbiology. John Wiley, pp. 2661–2674.
Wilson, J., Savage, D., Bond, A., Watson, S., Pusch, R., Bennett, D., 2011. Bentonite: A Review of Key Properties, Processes and Issues for Consideration in the UK Context. Quintessa, SWECO and TerraSalus Report, No: QRS-1378ZG-1, Version 1.1.
Wiseall, A.C., Cuss, R.J., Graham, C.C., Harrington, J.F., 2015. The visualization of flow paths in experimental studies of clay-rich materials. Mineral. Mag. 79 (6), 1335–1342.
Wogelius, R.A., Milodowski, A.E., Field, L.P., Metcalfe, R., Lowe, T., van Veelen, A., Carpenter, G., Norris, S., Yardley, B., 2020. Mineral reaction kinetics constrain the length scale of rock matrix diffusion. Sci. Rep. 10 (1), 8142.
Woodcock, N.H., 1984. Early Palaeozoic sedimentation and tectonics in Wales. Proc. Geol. Assoc. 95 (4), 323–335.