Radioactive Waste Management

NDA Report no. DSSC/453/01

Geological Disposal

Geosphere Status Report

December 2016

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ISBN 978-1-84029-566-5

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Abstract

The Geosphere Status Report is part of a suite of eight research status reports. The purpose of the research status reports is to describe the science and technology underpinning geological disposal of UK higher activity wastes by providing a structured review and summary of relevant published scientific literature and discussing its relevance in the UK context. The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal. The current suite of research status reports (issue 2) updates and replaces the suite produced in 2010 (issue 1).

This report provides a summary of the contribution of the geosphere as part of a multiple-barrier concept for geological disposal of radioactive waste, providing supporting evidence showing how the geosphere isolates and contains the wastes in order to assure long-term safety. It also explains how we can use our understanding of the properties of the geosphere and its expected evolution over the time periods of relevance to build confidence in the safety of geological disposal.

Executive summary

The Geosphere status report is part of a suite of research status reports describing the science and technology underpinning geological disposal of UK higher activity wastes.

The UK 2014 White Paper, Implementing Geological Disposal, set out the policy framework for managing higher activity radioactive waste in the long term through geological disposal, which will be implemented alongside ongoing interim storage and supporting research. It also established a revised Geological Disposal Facility (GDF) siting process and 'Initial Actions' to be undertaken by the UK Government and devolved administrations[1], and the developer, Radioactive Waste Management (RWM), before the siting process begins.

A Disposal System Safety Case (DSSC) considers the safety of radioactive waste transport to a Geological Disposal Facility (GDF), the safety of the construction and operation of the GDF, and the safety of the facility in the very long term, after it has been sealed and closed. A DSSC is in the early stages of development, because a site and design have not yet been chosen. We call it a 'generic' safety case, and the strategy to demonstrate safety is also termed 'generic' because it must cover a range of possible disposal environments and facility designs. Nevertheless, this work builds on more than 25 years of experience studying geological disposal and undertaking safety assessments in the UK. It also draws on the extensive body of knowledge and experience in other countries, gained through overseas radioactive waste management programmes.

The generic DSSC consists of an overview report, describing the safety of a geological disposal system; three main documents, one for each of the three components of the overall safety case, the Transport Safety Case, the Operational Safety Case, and the Environmental Safety Case, together with a series of supporting documents. This is such a supporting document, detailing our knowledge of aspects of the geosphere relevant to the DSSC.

The approach that we have taken until such time as more specific information becomes available is to define three host rocks that have already been identified as being potentially suitable for the geological disposal of high heat generating waste and low heat generating waste, and that are the focus of GDF development in several other countries. There are many different geological settings in England, Wales and Northern Ireland that may potentially be suitable for the GDF. Government policy is that the site selection process for the GDF will be consent-based. This means that any geological settings available for the GDF will depend on the locations of 'candidate sites' identified through discussions with local communities involved in the process. Potential host rocks are:

- Higher strength rocks (HSR), which may be igneous, metamorphic or older sedimentary rocks, have a low matrix porosity and low permeability, with the majority of any groundwater movement confined to fractures within the rock mass.
- Lower strength sedimentary rocks (LSSR) are fine-grained, sedimentary rocks with a high content of clay minerals that provides their low permeability and are mechanically weak, so that open fractures cannot be sustained. They will be interlayered with other sedimentary rock types. Although they have low permeability, LSSR may have significant water content in pores that are so small that water cannot flow through them. They are of interest both as potential host

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[1] UK Government in this context means the Department for Business, Energy and Industrial Strategy (BEIS). The devolved administrations are the Welsh Assembly Government and the Department of the Environment Northern Ireland. Scottish Government policy is that the long term management of higher activity radioactive waste should be in near surface facilities and that these should be located as near as possible to the site where the waste is produced. The Scottish Government therefore did not sponsor the 2008 or 2014 White Papers.

rocks and as potential seals providing additional containment above the GDF hosted in underlying rocks.

- Evaporite rocks have formed as ancient seas and lakes evaporated and often contain bodies of halite that provide a suitably dry environment and are weak and creep easily, so that open cracks cannot be sustained.

This report discusses the possible future behaviours of the geosphere in the context of these three potential host rocks.

There are two high-level principles of geological disposal of radioactive waste, namely to isolate the waste from the biosphere and to contain the radionuclides associated with the wastes. In order to assure that these objectives of isolation and containment are delivered over the long timescales of interest, geological disposal facilities are designed as multiple barrier systems. This involves designing engineered barriers that will work together and in combination with the natural barrier afforded by the geosphere to prevent radionuclides being released to the surface environment in amounts that could cause harm to life and the environment.

The geosphere contributes to isolation by providing a stable location deep underground that protects the GDF from any perturbations to the natural environment that may occur over the timescales of interest. This shields the surface environment from waste-derived irradiation and considerably reduces the risks of both intentional and inadvertent human disturbances and intrusion.

The geosphere contributes to containment by delaying the movement of any potential small amounts of long-lived radionuclides that are released from the engineered barrier system (EBS). The geosphere can fulfil its containment role in different ways. In the case of an evaporite, the key feature is the virtual absence of water as a transport medium. In many other geological settings, and recognising the role of surface topography, it is the slow movement of groundwater and geochemical retardation or immobilisation that ensures long travel times for some radionuclides released from the GDF, thereby facilitating their radioactive decay within the geosphere.

A suitable geological environment is fundamental to geological disposal. A site should be geologically stable in order to ensure safety and also be predictable to the extent required for assessing performance. A stable geological environment is one that is not likely to be subject to sudden or rapid detrimental changes over long timescales because of its buffering capacity with respect to internal and external perturbations. In the context of geological disposal, a site is considered to be geologically stable if perturbing geological events and processes can either be excluded, or shown to be sufficiently rare, slow or the consequences sufficiently small that safety will not be compromised over the required time frame.

The natural processes which may impact on the geosphere in a UK geological setting over the timescale of the next million years or so, which is particularly relevant to geological disposal, are tectonics, uplift or subsidence and erosion, and the impacts of future climate, particularly potential future glaciations. These natural processes and their potential impacts in the three illustrative geological settings are described. From historical knowledge and research, these processes are understood; therefore their impacts can be predicted with confidence. Furthermore, the geosphere at the depths under consideration for the GDF (between 200m and 1,000m below ground level) is less dynamic than shallow geological or surface environments. Processes generally occur more slowly at depth, therefore reliable predictions of long-term behaviour and evolution can be made.

Currently, we are at an early, ‘generic’ stage in the siting process, and no potentially suitable candidate site(s) for the GDF have been identified. Our geosphere programme involves participation in international projects, our own R&D programme and generic modelling studies. In the future, one or more of the candidate sites will be characterised to determine whether it is suitable to host the GDF. Therefore the site characterisation process is described and how it is used to develop understanding of the geosphere outlined.

This report will be updated, in line with updates to the DSSC, as part of each major stage of the GDF development programme. Over time, the design options under consideration and the choices RWM has to make will change from an emphasis on strategy to one of implementation. This approach is consistent with a staged development and approval process.

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List of Acronyms

ADZ	Alkaline Disturbed Zone
Andra	French National Radioactive Waste Management Agency
AP	After Present
BFS	Blast Furnace Slag
BGS	British Geological Survey
BIIS	British-Irish Ice Sheet
BP	Before Present
CDZ	Chemically Disturbed Zone
CPM	Continuum Porous Medium
CSH	Calcium Silicate Hydrate
DFN	Discrete Fracture Network
DNLEU	Depleted Natural and Low Enriched Uranium
DRZ	Disturbed Rock Zone
DSSC	Disposal System Safety Case
EBS	Engineered Barrier System
ECPM	Equivalent Continuous Porous Medium
EDZ	Excavation Disturbed Zone
EDZ / EdZ	Excavation Damaged Zone / Engineered Disturbed Zone (in context of certain WMO nomenclature, ex UK)
EIA	Environmental Impact Assessment
EMIC	Earth Models of Intermediate Complexity
EPM	Equivalent Porous Medium
ESC	Environmental Safety Case
FEP	Features, Events and Processes
GDF	Geological Disposal Facility
GIA	Glacial Isostatic Adjustment
GIF	Glacially induced faults
GRIP	Greenland Ice Core Project
GSHAP	Global Seismic Hazard Assessment Program
HHGW	High Heat Generating Waste
HSR	Higher Strength Rocks
HLW	High Level Waste
ILW	Intermediate Level Waste
ISO	International Organisation for Standardisation (EN-ISO indicates adoption of an ISO document by the European Union)
ISRM	International Society for Rock Mechanics

LGM	Last Glacial Maximum
LHGW	Low Heat Generating Waste
LLW	Low Level Waste
LSSR	Lower Strength Sedimentary Rocks
Nagra	Swiss National Cooperative for the Disposal of Radioactive Waste
NDA-RWMD	Nuclear Decommissioning Authority Radioactive Waste Management Directorate
NEA	Nuclear Energy Agency
ODP	Ocean Drilling Project
ODZ	Oxidised Disturbed Zone
ONDRAF-NIRAS	Belgian National Agency for Radioactive Waste and Enriched Fissile Material
OPC	Ordinary Portland Cement
PCSA	Post Closure Safety Assessment
PFA	Pulverised Fly Ash
PGR	Post Glacial Rebound
Posiva Oy	Expert organisation responsible for the final disposal of Finland's spent nuclear fuel
SDM	Site Descriptive Mode
SESAME	Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin
SF	Spent Fuel
SKB	Swedish Nuclear Fuel and Waste Management Company
UCS	Unconfined Compressive Strength
URL	Underground Research Laboratory
WIPP	Waste Isolation Pilot Plant
WMO	Waste Management Organisation

1 Introduction

1.1 Background

In order to build confidence in the safety of a future geological disposal facility (GDF) for the UK[2], in the absence of potential disposal sites, RWM is developing a generic Disposal System Safety Case (DSSC), which shows how the waste inventory destined for geological disposal could be safely disposed of in a range of geological environments. Background information on geological disposal in the UK can be found in the Technical Background Document [1].

The documents comprising the generic DSSC are shown in Figure 1 and include a number of research status reports ('Knowledge Base'). The purpose of the research status reports is to describe the science and technology underpinning geological disposal of UK higher activity wastes by providing a structured review and summary of relevant published scientific literature and discussing its relevance in the UK context. The current suite of research status reports (issue 2) updates and replaces the suite produced in 2010 (issue 1).

Figure 2 shows how research status reports underpin different safety cases. They include:

- reports on waste package evolution [2], engineered barrier system (EBS) evolution [3], and the geosphere [4] (this report), describing our understanding of the evolution of the specific barriers of the multi-barrier system
- reports on behaviour of radionuclides and non-radiological species in groundwater [5] and on gas generation and migration [6], describing the release and movement of materials through the multi-barrier system, including the groundwater and any gas phase formed
- reports on criticality safety [7] and on waste package accident performance [8], describing the behaviour of waste packages and the GDF during low probability events
- a report on the biosphere [9], describing how we think the biosphere may evolve in the future and how radionuclide uptake might be expected to take place.

Research status reports need to be read in conjunction with other documentation, including:

- the Data Report [10], which describes the values of specific parameters used in the safety assessments based on scientific information presented in the status reports
- the Science and Technology Plan [11], which describes planned research and development activities.

1.2 Objectives and scope

The objective of the Geosphere Status Report is to summarise the supporting evidence showing how the geosphere isolates and contains the wastes in order to assure long-term safety. There are many different geological settings in England, Wales and Northern Ireland that may potentially be suitable for the GDF.

This report provides a summary of the contribution of the geosphere as part of a multiple-barrier concept for geological disposal of radioactive waste. It also explains how we can use

[2] Disposal of higher activity radioactive wastes in a GDF is current policy in England, Wales and Northern Ireland. Scottish Government policy is that the long-term management of higher activity radioactive waste should be in near-surface facilities. Facilities should be located as near to the sites where the waste is produced as possible.

our understanding of the properties of the geosphere and its expected evolution over the time periods of relevance to build confidence in the safety of geological disposal.

The scope covers all materials currently considered in the inventory for disposal, including Intermediate and Low Level Waste (ILW/LLW), High Level Waste (HLW), spent fuels, uranium (particularly depleted, natural and low-enriched uranium, DNLEU) and plutonium.

Available information is discussed with the aim of providing a sufficiently detailed evaluation of the implications of key processes to allow its direct use in the development of safety cases. Safety-related considerations are excluded from the scope of this document and are provided solely in the safety cases.

Figure 1 Structure of the generic Disposal System Safety Case (DSSC). The suite of research status reports represents the knowledge base

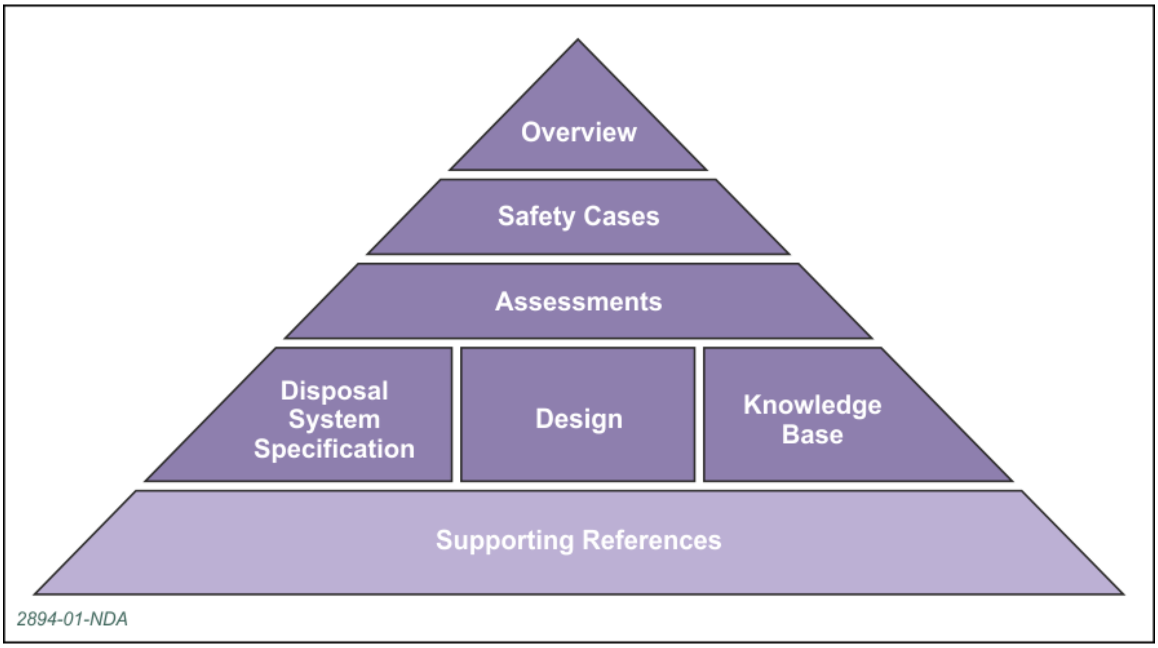
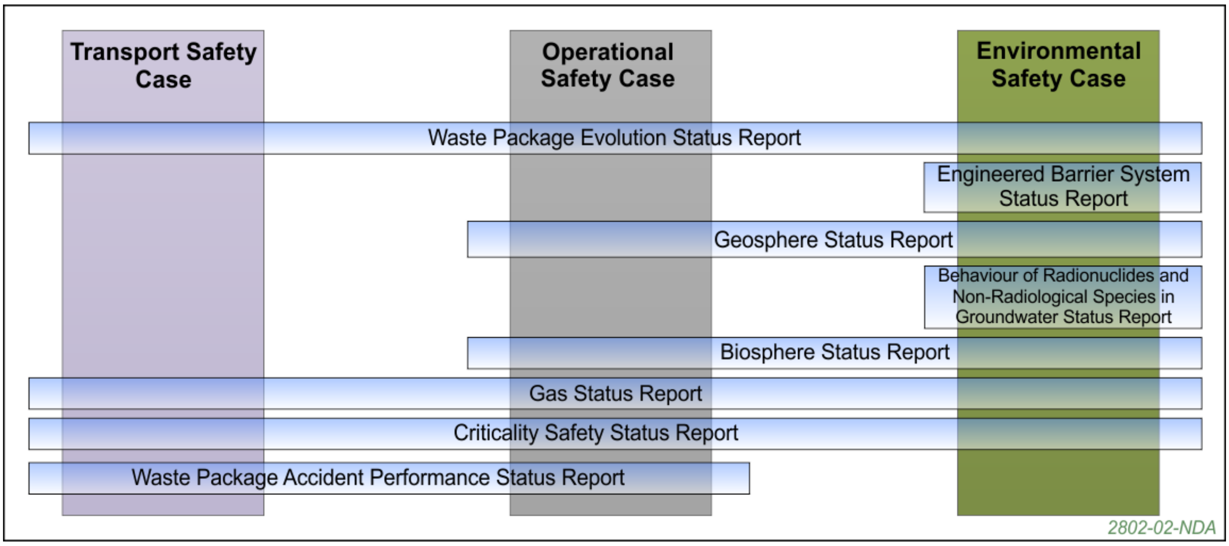


Figure 2 Safety cases and status reports in which underpinning information can be found



1.3 Audience and users

The primary external audience of the status reports is our regulators. The audience is also expected to include academics, learned societies and stakeholders such as the Committee on Radioactive Waste Management (CoRWM) and Non-Governmental Organisations (NGOs). The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal. The primary internal user of the information presented in the status reports is RWM's safety case team.

1.4 Relationship with other status reports

The migration of gases through the geosphere is discussed in the Gas Status Report [6] and the behaviour of radionuclides in the geosphere is discussed in the Behaviour of Radionuclides and Non-radiological Species in Groundwater Status Report [9]. In the GDF there will be interactions between processes occurring in the geosphere and processes occurring in the EBS, and between processes occurring in the geosphere and processes occurring in the biosphere. The Engineered Barrier System Status Report [3], Biosphere Status Report [9] and Geosphere Status Report are therefore interdependent, and the generic Environmental Safety Case [12] integrates the understanding documented in these status reports to describe how the man-made and natural barriers will interact and act to prevent the migration of radionuclides, whether in aqueous or gaseous form.

1.5 Changes from the previous issue

The generic DSSC was previously published in 2010. There are now a number of drivers for updating the safety case as an entire suite of documents, most notably the availability of an updated inventory for disposal [13].

This document updates and replaces the 2010 Geosphere Status Report [14], published as part of the 2010 generic DSSC suite. This issue includes the following improvements:

- an expansion of the section on natural processes and potential impacts on the geosphere
- an expansion of the section on GDF-induced impacts on the geosphere
- an update using new information from R&D programmes, including underground research laboratory-based experiments in a range of geological environments
- UK geology is introduced and illustrative geological environments are described for use in the generic DSSC
- a section discussing how developing understanding of the geosphere can be progressed is presented, describing how we are planning to characterise a site and the way in which modelling will be used to interpret site information.

In line with the objectives of the document and in order to respond to previous feedback, contextual and safety-related information have been removed from the text. Contextual information is provided in [1], while safety-related information is described entirely in the safety case documentation.

1.6 Knowledge base reference period

The knowledge base described in this document contains scientific information available to RWM up to March 2016. Where, within RWM's research programme, progress relative to important topics was made after such date, efforts have been made to reflect such progress up to the publication date of this document.

1.7 Terminology

A glossary of terms specific to the generic DSSC can be found in the Technical Background [1]. When necessary, we have introduced specific terminology used in the document through the use of footnotes.

1.8 Document structure

This report is structured according to the following format:

- section 2 discusses the role of the geosphere in the context of the GDF, and the geological attributes that have been defined in support of the siting process of the UK Government and devolved administrations, facilitating an assessment of the potential suitability of a candidate site
- section 3 provides a general discussion of components of the geological environment as relevant to the UK, noting such environments could be considered in a site selection programme for a UK GDF. As the siting process progresses, considerable further work relating to UK geology will be undertaken
- section 4 considers future large-scale natural processes that could affect a UK GDF, and their potential implications
- section 5 builds on components of the geological environment as discussed in section 3, and outlines six illustrative UK-relevant geological environments. These environments will be considered further in the generic DSSC, for example in the generic Environmental Safety Case
- section 6 considers how the GDF and its post-closure evolution could affect the geosphere
- section 7 briefly discusses how understanding of the geosphere is attained
- section 8 provides concluding remarks.

We have used coloured boxes at the beginning of each section to provide a short summary of the key messages and help the reader in following the ‘golden thread’.

2 Geological barrier

A suitable geological environment is a fundamental requirement for the viability of geological disposal. The geological environment is the term used to describe the rocks surrounding the GDF and includes the immediate and wider geological setting around the facility, including any geological structures and processes that affect these rocks and their associated hydrogeological, hydrochemical, geotechnical, thermal and radionuclide transport properties. Together, these control the behaviour of the geological environment and are key factors in determining the suitability and performance of a potential site as the GDF host.

A site should be both geologically stable, and also predictable to the extent required for assessing performance. A stable geological environment is one that is not likely to be subject to detrimental natural changes over long timescales. In the context of geological disposal, a site is considered to be geologically stable if perturbing geological events and processes can either be excluded, or shown to be sufficiently rare, or slow, or the consequences sufficiently small that safety will not be compromised over the required time frame [15]. The geological environment must also ensure isolation of the radionuclides in the waste, which is achieved by the combination of the properties of the host rocks and the rocks above and around them, and the present and likely future groundwater conditions. Not only must the waste remain contained by the geosphere into which it is emplaced, radionuclides must not be transported from the waste to the near-surface environment [5].

A site also needs geological units that are sufficiently homogeneous to display the characteristics of interest throughout an appropriate volume. A host rock needs to be of sufficient thickness and areal extent that the GDF could be constructed in it, whilst leaving undamaged host rock around it.

The geosphere at depths under consideration for the GDF, that is, a depth of between 200 m and 1,000 m, is generally less dynamic than shallow geological environments or surface environments. Natural processes that operate on rocks at depth are much less active than those that affect the near-surface, and estimations of long-term behaviour and evolution can be made with more confidence.

2.1 Geological topics and geological attributes

Geological attributes have been defined in support of the siting process of the UK Government and devolved administrations, facilitating an assessment of the potential suitability of potential candidate sites.

The effectiveness of a geological barrier depends not just on the host rock, but also on a range of other geological factors.

As part of the work on National Geological Screening set out in the 2014 White Paper, Implementing Geological Disposal [16], RWM has derived a number of geological attributes [17]; characteristics of the geological environment that are relevant to the long-term safety requirements. They may be characteristics of either the rock or the groundwater or may relate to geological processes or events and are intended to help identify information that is relevant to the suitability of a region as a potential host for the GDF. As such, they provide a convenient framework for synthesising geological information that is relevant to understanding the geosphere in general and geological barriers in particular, although it must be stressed that they do not cover all the issues that will be important when more detailed work on siting is undertaken.

The geological attributes proposed in RWM's guidance for National Geological Screening [17] have been grouped into five topics selected to encompass the characteristics of the geological environment:

1. rock type

2. rock structure
3. groundwater
4. natural processes
5. resources.

The five topics are used to structure a description of the relevant geological attributes, and are described in more detail in each of the following sub-sections. Subsequent sections of the current report provide information on components of the geological environment, as relevant to the UK, that inform our knowledge base of the above geological attributes.

2.1.1 Rock type

There is widespread agreement on the types of rock that may provide a suitable host for the GDF. These comprise higher-strength rocks, lower-strength sedimentary rocks and evaporites.

There has been widespread international agreement on the types of rock that may provide a suitable, low permeability host for the GDF for many years. From a general geology perspective, low permeability geological formations can be subdivided into three idealised categories [18]: 'hard rocks' such as igneous and metamorphic rock; 'soft rocks' such as clay and mudstone; and 'evaporite'. In detail, however, these geological classifications do not map exactly onto the properties which determine whether a rock is a potential host rock and, if it is, what safety case will be appropriate. Here, the focus is on grouping potential host rocks according to the different types of safety case that are appropriate for the different rock types rather than their geological origins. In common with most other national waste management organisations, we use a three-fold division of potential host rocks.

- Higher strength rocks (HSR), which may be igneous, metamorphic or older sedimentary rocks and have a low matrix porosity and low permeability, with the majority of any groundwater movement confined to fractures within the rock mass.
  - HSR typically comprise crystalline igneous, metamorphic rocks or geologically older sedimentary rocks. Unweathered granite is a good example of a rock that would fall into this category. In geological terms, a rock mass comprising 'higher strength rock' might not be a single rock type in petrological terms, provided the different rocks present have similar mechanical properties (for example the different components of a composite igneous intrusion). In contrast, a bed of HSR sedimentary rock interlayered with weak and fractured beds would not be suitable. A key characteristic of higher strength rocks is that they are relatively brittle and will contain fractures, although these may be sealed by mineral growth.
  - HSR in a geological disposal context describes rocks which have high strength but low permeability and in which any appreciable radionuclide transport will be by groundwater advection through fractures (not all rocks that fall into the engineering classification of 'high strength rocks' meet the requirements for geological disposal). Because of the importance of fractures for fluid flow, permeability measured by field tests is usually much greater than that determined by laboratory tests on intact core samples. Higher strength rocks that exhibit significant bulk permeability would be unsuitable as host rocks unless an adjacent rock was able to provide isolation from the near-surface environment.
  - HSR host rocks as defined by RWM are being considered in Sweden, Finland and Canada.

- Lower strength sedimentary rocks (LSSR) are fine-grained, sedimentary rocks with a high content of clay minerals that provides their low permeability and are mechanically weak, so that open fractures cannot be sustained. They will be interlayered with other sedimentary rock types. Although they have low permeability, LSSR may have significant water content in pores that are so small that water cannot flow through them. They are of interest both as potential host rocks and as potential seals providing additional containment above the GDF hosted in underlying rocks.
    - LSSR describes rocks which have low to moderate strength and contain a high proportion of clay. Any movement of water or dissolved chemical species is dominated by diffusion through the rock matrix because any fractures that develop in these rocks will self-seal. In the UK, this category includes clay and mudstone-dominated formations similar to the examples described in Section 3.
    - LSSR host rocks are being considered in France and Switzerland. Such rocks have sufficient strength to allow excavation of the GDF, provided appropriate engineering support is provided. They may undergo brittle failure, but they are also able to creep to some degree so that fractures would not be able to act as flow paths in the long term.
- Evaporite rocks have formed as ancient seas and lakes evaporated and often contain bodies of halite that provide a suitably dry environment and are weak and creep easily, so that open cracks cannot be sustained.
    - Evaporites are sedimentary rocks formed directly from the evaporation of surface water and commonly include abundant halite, further described in Section 3, and beds of other minerals formed by evaporation, notably sulphate minerals. Other rock types present may include mudrocks, marls and dolomitic limestone. Halite merits a distinct safety case because it provides a dry environment that will not be infiltrated by water and because any cracks will be self-sealing over time scales appropriate to geological disposal. Halite may occur as layers (beds), or may have been mobilised in the subsurface to form large diapirs or domes of halite that penetrate younger formations. An analogous safety case is not applicable to most evaporite rocks or minerals (such as dolomite or anhydrite), because these may contain water and would not have the required self-sealing properties. Salt domes do not occur within the area of interest (herein England, Wales and Northern Ireland), so an evaporite host rock would be a bedded evaporite.
    - The Waste Isolation Pilot Plant in USA is currently being operated in a halite host rock.

HSR, LSSR and Evaporite are referred to herein as ‘rock types of interest’, in recognition of the fact that, while all are potential host rocks, some may alternatively provide essential containment to the GDF hosted in underlying rocks. Section 3 provides further information on rock types of interest, while examples of schemes in other countries that employ these rock types as hosts are summarised below in Section 2.5.

Some common rock types are unlikely to be suitable to host the GDF in a UK context, because for example:

- They are unlikely to form homogeneous bodies of sufficient thickness and volume
- They are too permeable.

Nevertheless, such rocks could overlie or surround a host rock, and may lie on any groundwater return path from the GDF to the land surface. They will provide additional isolation and could provide some additional degree of containment. There rocks are referred to herein as ‘other significant rock types’.

Specific minerals present in all rocks along any groundwater flow path are also important; some retard the transport of specific radionuclides.

2.1.2 Rock structure

Complex rock structures may make it difficult to characterise a site sufficiently to demonstrate safety. In some circumstances rock structures may provide pathways for focussed groundwater flow, either along a structure itself or along specific rock units caught up in the structure.

The three-dimensional form and arrangement of different rock types and particularly the presence of geological features at depth, such as folding, faults and highly-fractured zones, may influence the uniformity and predictability of rock properties and groundwater flow. In the UK, these structures were invariably formed in the geological past. Active deformation today is considered under the topic “Natural Processes”, see Section 2.1.4.

Rock structure is principally of concern for two reasons: complex structures may make it difficult to characterise a site sufficiently to demonstrate safety, while in some circumstances rock structures may provide pathways for focussed groundwater flow, either along a structure itself or along specific rock units caught up in the structure. Rock structures may be the result of brittle or ductile deformation, or a combination of both. Faults may be simple brittle structures, but where there are large displacements, they are often composite structures with multiple fault planes. Where displacement of rock bodies has involved a component of ductile deformation, fault planes are replaced by shear zones in which the deformation is spread over a finite width, sometimes without any discontinuity. The final type of rock structure is folds. In metamorphic rocks, these may develop pervasively through large rock masses and often will not result in new zones of enhanced permeability, but in sedimentary sequences, folds may be closely associated with faulting and may have a major impact on groundwater flow by changing the orientations of layers with contrasting permeability.

Rock structure is considered in further detail in Section 3.2.

2.1.3 Groundwater

Groundwater saturates the pores and fractures in the majority of rocks below a few tens of metres in the UK. Permeability is a measure of the ability of a rock to transmit fluid. Fluid movement only occurs if there is a gradient in hydraulic head across a region, caused by gravity or thermal effects.

Groundwater is of concern in relation to the GDF as it may facilitate the movement of radionuclides. Groundwater saturates the pores and fractures in the majority of UK rocks below a few tens of metres depth and, where these pores and fractures are interconnected, water can move through the rock formations. Hydraulic conductivity is a parameter that measures the ease with which water will move through a rock in response to a given applied force. Because hydraulic conductivity is dependent on fluid properties as well as rock properties, and these may vary, for example as a result of differences in salinity, we prefer to use permeability as a measure of the ability of a rock to transmit fluid. Permeability is purely a rock property. Fluid movement only occurs if there is a gradient in hydraulic head across a region, for example if the water table is higher in one part of an area, perhaps because of the presence of higher ground, water will flow towards areas of lower hydraulic head.

Our knowledge of groundwater in the UK concerns the regions from which groundwater can be abstracted for consumption or agriculture, complemented by knowledge gained from water in mines and oil field brines. THE GDF will be sited at greater depths, beyond the reach of shallow potable groundwater circulation. There is less information about the composition and age of deep groundwaters or the hydraulic gradients present at GDF depths than is available for shallower groundwaters, and gathering such information will be an important early step in the siting process. In some parts of the country mineralised or warm water springs are indicative of the movement of deep groundwaters towards the surface. Clearly, flow systems that indicate connectivity between GDF depths and shallow groundwater (for example, hot springs) point towards areas that are probably unsuitable to host the GDF.

In addition to physical aspects of flow, groundwater chemistry is also very important for developing a safety case for the GDF because engineered barriers must be designed to be compatible with it. Again however, for most parts of the country we have limited-to-no information about the composition of groundwater at GDF depths.

Understanding groundwater behaviour is an extremely important aspect of the GDF siting process, and further details on its importance are provided below in Section 3.3.

2.1.4 Natural processes

Sea-level change, erosion, earthquakes, regional uplift and the growth and retreat of ice sheets and glaciers are processes that are relevant to maintaining the safety of the GDF over very long timescales.

Natural processes include both progressive changes, such as erosion, and sporadic isolated events, such as earthquakes; these may affect the geological barrier over the timescales of relevance to GDF safety.

A number of natural processes are relevant to maintaining the safety of the GDF over very long timescales because they could modify groundwater flow patterns or lead to the cover above the GDF being removed by erosion. Examples of such processes are sea-level change, erosion, earthquakes, regional uplift and the growth and retreat of ice sheets and glaciers. Such processes are influenced by tectonic stress and by long-term climatic drivers.

A change in sea level has the potential to influence groundwater movement around the GDF, particularly if the site has a coastal location. Sea water inundation inland could result in saline denser water overlying freshwater. Sea level rise reduces the hydraulic gradient and, depending on site-specific attributes, could reduce the likelihood of groundwater flow through the GDF; a drop in sea level could have the opposite effect.

Erosion of the land surface will result in a reduced thickness of the geological barrier above the GDF and mainly takes place in areas where there is regional tectonic uplift. Conversely, in areas of regional tectonic subsidence, sedimentation results in a thicker geological barrier over time.

During glacial episodes, the formation and decay of permafrost, glaciers and ice sheets drive enhanced erosion and influence the chemical composition and movement of deep groundwater. The development of permafrost affects the patterns and rates of water movement in the subsurface, as well as water composition, while the growth of ice sheets increases hydraulic head beneath the ice, potentially moving fresh groundwater to greater depths and setting up new flow patterns. However, in lower permeability environments the hydraulic effects of glaciation may be to lock in beneficial downward hydraulic gradients for long periods of time after the glaciers have retreated, effectively isolating shallow and deep groundwater systems.

Earthquakes (seismicity) result from the release of energy associated with sudden movement along existing faults, or (very rarely) the propagation of new faults. Faults may also move without earthquakes (aseismic creep). Most earthquake risk to engineered structures occurs at the Earth's surface, from shaking due to the propagation of surface waves. Shaking is strongly attenuated at GDF depths and deep underground structures suffer little from shaking damage, even in major seismic events. Significant fault movement in the vicinity of the GDF could physically damage the engineered barrier system if it results in centimetre-scale displacements in a network of small fractures in the GDF host rock, but the largest earthquakes in the UK take place at greater depths than proposed for the GDF and involve displacements of less than 1 mm. Mapped faults will be avoided in laying out the openings of the GDF, making it unlikely that individual vaults or tunnels could be directly cut by any future movement on existing faults.

2.1.5 Resources

Geological resources present at depth are primarily of importance because of the risk of inadvertent human intrusion during exploration or exploitation of resources in the future.

This topic concerns geological resources present or suspected to be present at depth and is primarily of importance because of the risk of inadvertent human intrusion during exploration or exploitation of resources in the future. It covers both deep-mined and intensely drilled areas where resources have been exploited in the past, and the presence of potentially exploitable resources (coal, hydrocarbons (including unconventional resources), metal ores and industrial minerals). Many resources that have been exploited in the past are considered relevant because most exploration for new resources often takes place around sites of past exploitation.

In order to look ahead, we have defined resources as unusually enhanced concentrations at depth of a specific element, mineral, liquid, gas or heat, which might reasonably be of value in the future and which cannot be sourced from locations closer to the surface. This definition includes resources that have not been shown to be economically viable, such as shale gas, coal-bed methane and geothermal resources, as well as possible extensions of reserves that are exploited today or have been exploited in the past. Whether or not a resource might be exploited by a future generation is very difficult to evaluate.

Information about past and present resource extraction from the depths of interest and deeper is available for England, Wales and Northern Ireland. For some of the most important types of mines (coal, iron) there are also data available on the likely deep extent of unmined material and it will be possible to produce maps of both known workings and known resources in the depth range of interest for the GDF.

Resources are considered in the Environmental Safety Case [12], contributory to the future human intrusion scenario, and are not considered further in this context in the Geosphere Status Report. However, exploited resources may have an impact on groundwater flow and in this guise they are discussed further in Section 3.3.

2.2 Approach of other waste management organisations

International approaches demonstrate that a range of rock-types is suitable to host the GDF and examples exist in higher strength rocks, lower strength sedimentary rocks and evaporite rocks.

The approaches of other waste management organisations (WMOs) to the development of the GDF have utilised examples of the host rock types introduced in the previous section and are briefly described here. WMOs in both Sweden and Finland have developed GDF concepts utilising HSR host lithologies. The Swedish nuclear waste and management company, SKB, has selected a site at Forsmark for the development of the GDF located at around 500 m depth in Palaeoproterozoic intrusive igneous rocks of the Fennoscandian Shield, an area that has been tectonically stable since at least Cambrian times (>485 million years ago) [19]. Similarly, in Finland, the Olkiluoto-proposed GDF site being developed by Posiva Oy is also part of the Fennoscandian Shield and comprises both intrusive igneous rocks and metamorphic rocks at a depth of around 600 m depth [20]. Rocks at both these sites have been affected by both ductile and brittle tectonic deformations in the geological past, as well as more recent, neotectonic deformation, and these have been the focus of much of the site investigation work [21].

WMOs in France and Switzerland have both developed GDF concepts in very low-permeability Jurassic mudrock formations. The French waste management authority Andra is considering a site in the eastern Paris Basin hosted by Jurassic Callovo-Oxfordian clay-rich sediments at a depth of around 500 m. These have been shown to be relatively homogeneous, with little disruption by geological faults and fractures and to have experienced very little groundwater movement [22]. Similarly, in Switzerland, the Jurassic Opalinus Clay has been identified as a suitable host rock. This formation is relatively uniform and extensively developed under northern Switzerland. In the areas under consideration, the Opalinus Clay is located at depths ranging from 200 m to 700 m [23].

In the USA, the Waste Isolation Pilot Plant (WIPP) in New Mexico has been developed in a Permian evaporite formation and has been operational since 1999. This GDF comprises caverns excavated at a depth of about 800 m in bedded rock-salt (halite) of the Permian Salado Formation [21]. Investigations in the Gorleben salt dome, Germany, at a planned depth of 840 m have been undertaken [24, 25] as part of a process to consider the suitability of this salt dome for the disposal of some of Germany’s radioactive waste inventory, and detailed proposals have been prepared.

Further information on the work of other WMOs worldwide is provided below in Section 7, and in particular in Sections 7.3 and 7.6.

3 Illustrative components of the geological environment

In this section, an account is provided of the contribution made by the key components of the geological environment, in particular geological materials, groundwater and hydrochemistry, to the long-term safety of the GDF. Together, these components control the behaviour of the natural geological barrier and determine its suitability and performance as part of the GDF. This is accompanied by a description of the summary properties from a range of geological materials (lithologies and formations) in England, Wales and Northern Ireland, including the mechanisms of groundwater movement and relevant aspects of hydrochemistry, illustrated with well-documented examples.

3.1 Rock types and their related properties relevant to construction and post-closure safety of the GDF in England, Wales or Northern Ireland

The UK is made up of a wide variety of rock types, many of which could provide suitable host rock environments for the GDF.

The approach taken in this section is to provide further details of rock types introduced in Section 2, in the context of the geological environments likely to be encountered in the subsurface of England, Wales or Northern Ireland to a depth of around 1000 m. These rocks represent the fundamental building blocks of the geological environment and contribute in different ways to the overall safety functions of containment and isolation of the waste and the construction characteristics of a multi-barrier GDF, dependent on the local geology at the site. The engineering design of the GDF will be tailored to suit the specific characteristics of the host rock and its geological setting once a potential site has been evaluated.

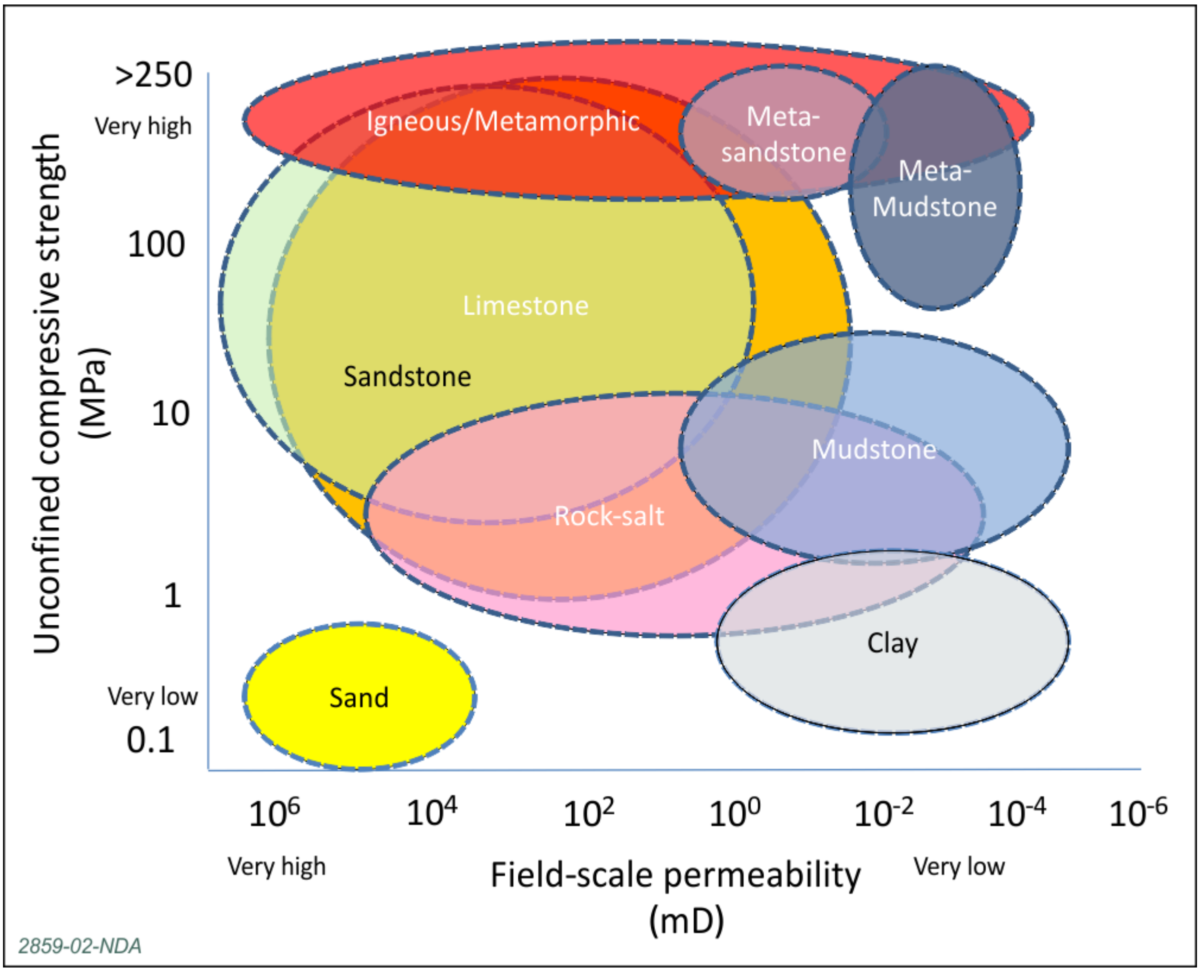
In order to illustrate the properties of the range of rock types that are potential host rocks, we have developed a conceptual descriptive framework that seeks to place a variety of common rock types in a matrix in which the axes represent variation in the key properties of permeability and strength (Figure 3).

The rock types shown are generalised from subdivisions represented on the British Geological Survey (BGS) 1:1 000 000 series engineering geology (bedrock) map of the UK [26] wherein they are related to lithological descriptions, including strength (after BS5930: 1999 [27]).

Strength is described and classified in accordance with ISO 14688 parts 1 and 2 respectively [28, 29]. In this section, the widely used descriptor of Unconfined Compressive Strength (UCS) to classify rock strength at the surface or near-surface is adopted. The rock strength description and terms are described in EN ISO 14689-1 [30] and follow practice and terminology outlined in International Society for Rock Mechanics (ISRM) [31] suggested methods[3]. In addition, it is important to recognise that the properties of rocks under pressure, at GDF depths, may differ significantly from their surface properties, especially in their ability to develop and sustain open fractures. For example, mudrocks that may be fractured in the near surface, and have a significant permeability as a result, may be unable to sustain open fractures at GDF depths.

[3] Note that in Section 2 we presented RWM-originated descriptions of higher strength rocks, lower strength sedimentary rocks and evaporites. It is recognised that there are instances in which rock strength, as classified by the UCS system for certain rock types, and how RWM terminology describes the same rock types differ. This is a manifestation of the UCS system relating to rock engineering classification, and RWM terminology relating primarily to groundwater movement.

Figure 3 Indicative matrix of mechanical strength versus field scale permeability for key UK lithologies. This is based on near surface determinations (both strength and permeability are likely to vary on the scale of the GDF dependent on distribution and density of secondary (fracture) permeability). Note: Limestone is shown in orange and sandstone shown in green. Both pristine and weathered rocks are included.



The fields in Figure 3 representing the common rock types are based on the recognition of broadly contrasting divisions of both original lithology (rock type) and processes that may have modified them, including diagenesis and metamorphism since deposition. While not exhaustive, these fields are believed to cover most of the natural variability in potential host rocks for a potential GDF site in England, Wales and Northern Ireland between 200 m and 1000 m depth and occurring in sufficient volume for construction purposes. Properties of adjacent rocks that could potentially contribute to the safety case for the GDF in an adjacent rock are also included. The information on permeability presented here is mainly derived by techniques which are not very sensitive for low permeability rocks. Some of the measurements that yield relatively high values for their permeability are likely to have been made on weathered material near the surface and may not represent the properties of the same rock units at GDF depths. In recent years there have been considerable advances in the petrophysics of mudrocks and it is now possible to make high quality determinations of permeability on very low permeability materials, with a large data base, largely unpublished, on mudrocks of interest for unconventional hydrocarbon extraction. We anticipate that, if future investigations are carried out on laboratory and field scale permeability of mudrock units, the results are likely to be more tightly clustered and at the lower end of the range presented in this document.

The following Sections (3.1.1 to 3.1.9) summarise the range of lithologies of interest present in the area under consideration, largely based on surface and near-surface observations and properties. Potential changes in physical properties of rock at likely GDF depths are considered in the main descriptive part of the section, although details of failure mechanisms are not covered in detail. The 'sand' class illustrated in Figure 3 is not considered further, as this relates to unconsolidated sands (not sandstones), and in general 'sand' does not exist at GDF-relevant depths. 'Rock types of interest' are considered initially (Sections 3.1.1 to 3.1.6), 'other significant rock types' are considered in Sections 3.1.7 to 3.1.9.

For each of the rock classes, a concise systematic description is provided in order to convey the most typical compositional and structural characteristics, including:

1. lithological description, including mineral composition, texture, common penetrative structures and discontinuities
2. important facies subdivisions, heterogeneity and layering
3. key or characteristic geological / diagenetic history and consequences for properties of flow and transport
4. mechanical properties related to lithology
5. porosity-permeability characteristics
6. an overview of the hydrochemistry of typical groundwater.

In providing these detailed descriptions it is necessary to utilise illustrative information from well-understood examples in the UK geological record. Where such examples have been used, they are identified directly, although it should be understood that these are purely used for illustrative purposes and are not related to any site selection process.

3.1.1 Evaporite

Evaporites have formed as ancient seas and lakes evaporated and often contain bodies of halite that provide a suitably dry environment and are weak and creep easily, so that open cracks cannot be sustained. Other rock types present may include mudrocks, marls and dolomitic limestone.

Evaporite is the name given to the group of rocks that are composed of water-soluble mineral salts. They comprise a number of different minerals but are formed in two environments: marine evaporites that are precipitated from sea-water; and non-marine evaporites that form in terrestrial settings, largely by evaporation of ephemeral lakes. For the purposes of this section, the occurrence of evaporites comprising the chloride minerals rock-salt (halite) and potash (sylvite) are of interest because excavations in these minerals provide a dry environment, eliminating the possibility of fluid flow through the GDF. As a result, the safety case for the GDF hosted in salt is distinct from that for any other rock. Other evaporite minerals, including gypsum and anhydrite, are not considered here as they can retain open fractures through which fluid movement is possible over extended periods of time. It is however possible that a suitable body of sulphate could host the GDF based on a safety case appropriate for higher strength rock. In practice, sylvite is unlikely to be chosen to host the GDF because it is less abundant than halite, occurs in thinner layers, is weaker, so that it cannot support large excavations for extended periods of time, and also has far greater monetary value, increasing the risk of future human intrusion.

Rock-salt does not crop out at the surface in the UK because of its rapid dissolution by groundwater. The region where the salt would have cropped out, had it not been dissolved, is defined by a zone of collapse breccias of mudstones that originally overlay, or were interbedded with, the halite and is referred to as ‘wet rock head’.

Rock-salt may behave plastically in the shallow subsurface and has low porosity (< 0.1%), low primary permeability (10^{-6} to 10^{-5} mD (see footnote [4]) and field-scale permeability in the range <10^{-3} to 10^{4} mD (see footnote [5]). The fluids in rock-salt can be externally derived, that is, they may originate from below the salt succession or enter as meteoric waters from above. Alternatively, they may have been present inside the salt body, from the original burial and recrystallization of the salt, as fluid inclusions. Any fluids are brines with salinity at halite saturation. The preservation of halite over geological timescales requires that groundwater flow is negligible; any solute movement occurring is by diffusion. Adsorption of solutes to halite is generally very poor, except for a few radionuclides such as isotopes of Cl and Cs. Rock-salt is mechanically weak (UCS 5 to 25 MPa) and either mechanical excavation or dissolution methods are employed to create caverns to extract salt as a mineral resource or for underground gas storage. Existence of pre-existing voids (mines) and the ongoing value of rock salt as a resource are considerations in assessing the suitability of rock-salt as a GDF host rock. Engineered cavities at depth may be self-supporting but time-dependent creep/flow behaviour is a consideration. Rock salt is commonly inter-bedded with mudstones, anhydrite or dolomite, and in some circumstances these interbeds may contain brine under pressure.

In England, Wales and Northern Ireland, most rock-salt is preserved within rocks of Triassic or Permian age (Mercia Mudstone Group and Zechstein Group respectively), Triassic evaporites were deposited in a series of discrete terrestrial basins, the most extensive of which is the Cheshire Basin of central England and parts of Wales [32]. Here, the Mercia Mudstone Group largely comprises units of mudstone and siltstone that are locally interlayered with thin halite beds, but two significant halite units are present: the Northwich Halite Member, up to around 280m thick, and the Wilkesley Halite Member, up to around 400m thick [33]. Both rock-salt units are interlayered with units of mudstone with local occurrence of sandstone (Figure 4). Wet rock head generally extends down to 50-60 m, but has been recorded to depths of about 180 m [34], where collapse has been exacerbated by brine pumping.

A range of evaporite minerals, including halite and sylvite, are present in Permian (Zechstein Group) rocks of NE England ([35, 36]). Rock-salt typically occurs in beds associated with mudstone that range from a few centimetres to hundreds of metres thick. The Permian halites of the Zechstein Group were deposited in a rift system in an enclosed marine basin. The most extensively mined unit is the Boulby halite, from which sylvite is mined with halite as a by-product. At Hornsea in East Yorkshire, gas storage cavities have been created within the Fordon Evaporite up to around 100m high and at depths of up to 1800 m. Elevated groundwater heads during the Devensian (the most recent glacial period, occurring during the last years of the Pleistocene, 110,000 to 10,000 years ago) mean that the dissolution front and wet rock head extend to depths of 300-400 m [34].

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[4] A Darcy (or Darcy unit) and millidarcy (mD) are units of permeability, named after Henry Darcy. They are not SI units, but they are widely used in petroleum engineering and geology. Like some other measures of permeability, a darcy has dimensional units in $(length)^2$. Converted to SI units, 1 millidarcy is equivalent to 9.869233×10^{-16} m^2.

[5] Note that wide ranges in field-scale permeability reported herein reflect uncertainties based on limited numbers of field measurements and the variable impacts of fracture networks and interbeds that have influenced these field test results.

Figure 4 Core from Northwich Victoria Infirmary Borehole (SJ67SE/137), Triassic Northwich Halite Formation. Interlayered mudstone and halite (British Geological Survey © NERC 2014)

3.1.2 Mudrocks: clays and mudstones

Very fine grained sedimentary rocks can be generally referred to as mudrocks. Clay-rich sedimentary rocks which remain sufficiently weak that any fractures that develop in them will self-seal at GDF depths, so that fluids and solutes can only be transported through them by diffusion, are of interest as potential GDF host rocks.

This group of rocks consists of sedimentary rocks formed by the deposition of very fine grained particles, predominantly clay minerals. Very fine grained rocks in which the particles are not dominated by clay minerals are unlikely to have the characteristics required to ensure low permeability and so are not considered in this report, although silt-sized particles of minerals other than clays are normally present. Very fine grained rocks can be generally referred to as mudrocks, although there is no universally agreed classification. When first deposited, clay deposits are extremely weak and have a very high water content. With burial, they become compacted and the water content decreases; as a result, strength increases.

Many mudrocks have been buried to greater depths in the past and so have properties that appear anomalous for their present depth of burial; these rocks are referred to as over-compacted. This section describes the range of clay-rich sedimentary rocks which remain sufficiently weak that any fractures that develop in them will self-seal at GDF depths, so that fluids and solutes can only be transported through them by diffusion. Such rocks comprise the category of potential host rocks described earlier as Lower Strength Sedimentary Rocks (LSSR). In addition to their potential as host rocks, LSSR are also of significance because they can provide impermeable barriers separating the deep groundwater below from shallower groundwater above.

There are a range of clay minerals that may occur in sediments, but the predominance of smectite in many LSSR represents a significant design constraint for engineering projects because of its ability to absorb and release water from the clay lattice structure, giving rise to the potential for volume changes within the rock mass (shrink-swell behaviour).

Clay-rich sediments may also give rise to different chemical environments according to their origins. They occur as two main facies, oxic and dysoxic, largely reflecting the redox conditions in the depositional environment, and in particular the amount of organic matter deposited with the clay. Dysoxic mudrocks typically contain carbon-rich material derived from organic matter, and iron sulphide minerals. The main significance from the perspective of a geological barrier is that where organic matter is present, hydrocarbons may occur in the pores as well as water. The presence of iron sulphides can lead to geochemical and biogeochemical processes that generate sulphuric acid if the rocks are exposed to oxygen and so could cause deterioration of engineered barriers.

We note that mudrocks can contain sand lenses and channels, as well as injectite dykes caused as they compacted.

Clays

This class includes very fine-grained clastic sedimentary rocks (clay or claystone), that have not undergone significant sedimentary burial-related chemical or physical alteration since deposition (diagenesis). Clay formations are distinguished from mudstone by their higher water content and lower strength; despite often being over-consolidated they are generally mechanically very weak to weak (UCS 1.15 to 25 MPa), although strength and ductility will change with increasing depth dependent on pore pressure and local stress conditions. They may exhibit plastic deformation or creep behaviour at depth and have high porosity (40-70 %) but low primary and field scale permeability (10^{-5} to 1 mD). Groundwater flow is very slow (or negligible), and solute transport occurs mainly by difffusion. They have a marked capacity to adsorb and retain radionuclides. The groundwater within them is likely to be brackish. Due to the clays forming part of a mixed lithology sedimentary sequence, any groundwater flow is generally upwards or downwards towards more permeable over- or under-lying rocks respectively. Where characterised by plastic behaviour, any fractures present should not be transmissive. These materials are relatively easy to excavate but may be subject to creep, heave and shear failure and require support in engineered cavities. Clay may also be fissured, which can result in strength and permeability anisotropy.

These deposits are relatively extensive in parts of the south and east of England where they locally reach the shallower limit of GDF depths, and the following account relies principally on the well-studied geology around London where understanding of Cenozoic mudstone formations has been critical to large scale infrastructure projects [37, 38].

The Cenozoic clay formations tend to be relatively thin, of the order of 10's to more than 100 m thick and are typically interlayered with subordinate beds and units of sand and pebbly sand and, more rarely, shelly horizons and limestone deposited in a marginal marine environment. They comprise an oxic facies of weakly or unbedded clay and silty clay or may be thinly laminated with fine sand or silt partings. They are often bioturbated, or colour mottled with rootlet traces that provide evidence of subaerial exposure and the development of soils (pedogenesis; Figure 5). Locally, dysoxic (having a very low oxygen concentration) facies units of laminated clay are preserved.

Figure 5 Rootlet traces in the basal Reading Formation, Alum Bay (British Geological Survey © NERC 2014).

Reference [39] quotes porosities for Cenozoic clay of 43-48 % and intrinsic permeabilities of 10^{-2} and 4 x 10^{4} mD for two samples. At the formation scale permeability is increased by fracturing, and average values of 1 mD have been quoted for the London Basin [40]. A lower range of permeability values for London Clay, with 1 mD as the maximum field scale measurement, is noted in [41], where a range of laboratory experiment-derived permeabilities for London Clay of 10^{-2} to 10^{-5} mD is given. The range of field scale permeabilities for London Clay at 0-50 m depth given in [42] is 1 to 10^{-3} mD. The chemistry of groundwater from the London Clay at depths of between 5 and 57 m for a site at Bradwell indicates pH between 7 and 9, and variably high sulphate [43].

Mudstones

The term mudstone is used here to denote clay-rich clastic sediments that are more compacted and somewhat stronger than clays. It should be noted however that such rocks are often referred to as “clays”, for example in the French and Swiss programs. Mudstones are somewhat lithified having undergone alteration, such as growth of cement and recrystallisation of primary clay minerals during burial diagenesis. They generally have moderate to high porosity (10 to 40 %) but low primary and field-scale permeability (10^{-5} to 100 mD), with solute transport via diffusion and a marked capacity to adsorb radionuclides. As mudstones generally form part of a mixed lithology succession, any groundwater flow is generally upwards or downwards towards more permeable over- and under-lying rocks respectively.

Mudstones are typically weak to medium strong (UCS 5 to 50 MPa) and are moderately easy to excavate. They have a moderate propensity for heave; swelling and creep behaviour are likely at GDF depths and may require support in engineered cavities. With further burial and associated heating, mudstones evolve into shales, in which clay minerals are aligned, and become stronger with additional cementation. Mudrocks which have been more deeply buried are stronger but also more brittle and might retain open fractures for sustained periods. In this case, they would not fulfil the requirements for LSSR host rocks, and for the purposes of this report will be termed shales; they are discussed in the following section.

Mudstone with the characteristics of LSSR is a commonly occurring sedimentary rock, present primarily in rocks of Mesozoic age in the UK. It was typically deposited in marine basins although significant mudstone formations in the UK, including the aforementioned Mercia Mudstone Group, were deposited in terrestrial aeolian or lacustrine environments. Mudstone formations may vary widely in texture, from homogeneous to finely laminated and may be interlayered with other lithologies such as sandstone and limestone at all scales. Texture, composition and layering are strongly controlled by the depositional process and subsequent diagenesis.

For the purposes of this report, the mudstone class is illustrated by the Oxford Clay Formation. This is of Jurassic age and is broadly equivalent to the Callovo-Oxfordian clays under consideration for the French GDF project. It crops out in a broad swathe extending from the Dorset coast in the south of England, across the south Midlands and into East Anglia and, in a regional sense, dips gently toward the southeast and so is present at depth beneath younger rocks across much of the area to the south east of the outcrop. At its greatest it is more than 150 m thick, but becomes thinner toward the southwest and northeast. The formation is organic rich and abundantly fossiliferous throughout. The Oxford Clay Formation comprises a dysoxic facies with three lithologically distinctive members [44]. The lower Peterborough Member comprises greenish blocky mudstone with interbeds of fissile bituminous mudstone and locally persistent horizons of argillaceous micritic limestone (having a matrix derived from calcite mud) nodules and beds. This member, when accessible at outcrops, is an historically important brick clay resource (Figure 6).

Petrographic analysis of the Member reveals it to comprise largely quartz and illite (a clay), with subordinate chlorite and kaolinite (also clays), K-feldspar and plagioclase, and variable amounts of calcite and siderite [45]. The overlying Stewartby Member comprises pale grey calcareous mudstone, with scattered beds of silty mudstone and nodular limestone, some of which are fossiliferous. The upper Weymouth Member comprises poorly fossiliferous, slightly silty mudstone with subordinate calcareous siltstone beds and rare silty limestones. Selenite (gypsum) and pyrite are generally present as authigenic crystals and fissure coatings in the weathered zone in the top few metres of the formation. Calcite and authigenic quartz were also both locally precipitated during diagenesis [46].

Because of its low permeability (10^{-4} to 1 mD, [47]), the Oxford Clay does not represent an aquifer and generally yields little groundwater in boreholes. Where groundwater is produced it can be of poor quality (saline), although this is mitigated in the near surface by flushing with meteoric water [48]. Measurement of average groundwater heads in Oxfordshire indicates upwards movement into overlying more permeable strata [49]. Engineering considerations associated with the Oxford Clay Formation include concrete attack resulting from pyrite oxidation and shrink-swell behaviour.

Figure 6 King's Dyke Pit, Whittlesey, near Peterborough. Excavation in Peterborough Member of the Oxford Clay Formation (British Geological Survey © NERC 2014).

3.1.3 Metamudstone shales and slates

These are clay-rich rocks, typically older than mudstone in the UK, and have undergone significant post depositional modification. Fractures in metamudstone shales and slates are less likely to heal because of how their mineralogy has evolved; these rocks cannot be considered as potential lower strength sedimentary host rocks. Where thick, homogeneous bodies of slate occur they have the potential to act as higher strength host rocks.

These are clay-rich rocks, typically older than mudstone in the UK, and have undergone significant post depositional modification. Specifically, on the basis of illite crystallinity these rocks can be classed as late diagenetic or higher grade and this is the basis for referring to them as metamudstones. In shales, compaction due to burial has greatly reduced porosity and resulted in some alignment of platy clay mineral grains but the rocks lack the intense deformation of a slate and are generally weaker as a result. For our purposes, we interpret mudstones as potential LSSR hosts in which fractures will self-heal, while metamudstones are less likely to heal because of their coarser, recrystallised phyllosilicate mineral grains. Slates have undergone more extreme modification than shales, including further metamorphism and penetrative deformation to form folds and tectonic fabrics that have significantly changed the texture, strength and permeability characteristics from those of the precursor mudstones. Slates are typically strong to very strong (UCS 50 to 250 MPa) and can display strength anisotropy on the GDF scale where tectonic fabrics (slaty cleavage) are developed. Fractures in shales and slates are not self-sealing and so these cannot be considered as potential lower strength sedimentary host rocks. Where thick, homogeneous bodies of slate occur they do however have the potential to act as higher strength host rocks for the GDF and may be able to safely accommodate HSR disposal concepts.

Slate generally has low porosity (<5%) and low primary permeability (10^{-8} to 10^{-3} mD), with solute transport by diffusion at the core scale; field scale permeability is generally orders of magnitude higher due to the presence of fractures (10^{-4} to 10^{-3} mD). The range of permeabilities for shales is 10^{-9} to 10^{-3} mD (based on [50]). Other mudstone caprocks have permeabilities in the range 10^{-7} to 10^{-5} mD (based on [41]). Modelled intrinsic permeability of deep gas-bearing shale is approximately 0.1 to 0.4 mD [51].

Excavation is strongly influenced by discontinuity or fabric orientation and may require blasting. Engineered cavities at GDF depths may require support, depending on discontinuity strength, spacing and orientation relative to excavation and local stress conditions.

Most of the mudrocks in England, Wales and Northern Ireland that are classed as shales or slates are of Palaeozoic depositional age and the slates have been affected by Caledonian or Variscan deformation. The principal areas of exposure are in Wales, the south-west of England and Cumbria. However, the same slates extend east beneath younger cover sediments across large parts of England.

3.1.4 Extrusive igneous rocks

This class comprises erupted lavas and tuffs which are typically very strong, fractured rock. Solute transport is largely by advection. Dependent on the extent of fracturing, these formations may provide a suitable higher strength host rock environment.

This class comprises erupted lavas and tuffs (volcanic debris) including re-worked and redeposited tuffs. Many have experienced low grade metamorphism, both shortly after deposition and during subsequent tectonism, and are metavolcanic slates. They are typically very strong to extremely strong (UCS 100 to >250 MPa) with very low primary permeability (10^{-5} to 10 mD). Secondary fractures typically provide higher field-scale permeability (10^{-1} to 10^{6} mD) and solute transport is largely by advection. This permeability may be anisotropic because of the orientation of fracture systems. Some extrusive igneous rocks are more massive lava flows which are not always metamorphosed or deformed. Extrusive igneous rocks are likely to require blasting and may be self-supporting in deep engineered cavities, dependent on local stress conditions, fracture characteristics and strength.

In England and Wales, the occurrence of thick successions of extrusive igneous rocks is mainly limited to older, Lower Palaeozoic settings which outcrop principally in Pembrokeshire in West Wales, Snowdonia in North Wales and the English Lake District of Cumbria. They are often closely associated with metamudstone slates, described above, and are likewise believed to be present at depth beneath parts of the North Pennines and possibly other areas of eastern England.

Younger volcanic rocks are present in Northern Ireland, where there are extensive basaltic lava flows formed at the margins of the Tertiary Igneous Province. These consist of flows of hard, strong crystalline igneous rock, inter-bedded with rubbly, weathered material and sediment. In general, the flows are extensively fractured by cooling cracks. Thin vertical sheets of intruded basalt are also present.

For the purposes of this account, the well documented Snowdon Volcanic Group of North Wales and the Borrowdale Volcanic Group of Cumbria are used as examples of metavolcanic rocks [52, 53]. In north Wales these comprise an approximately 1100 m thick succession of two eruptive products from several individual volcanic centres which inter-finger with background marine and marginal marine sediments. The deposits themselves comprise 10’s to 100’s of metres thick units of rocks which were originally deposited as acid ash-flow tuff, basic tuff and a variety of fine to coarse grained tuffaceous clastic sediments, as well as basaltic lavas and rhyolite domes and breccias.

The volcanic units preserve a wide range of textures found in idealised ignimbrite flows [54]. Typically these include non-welded tuff, generally preserved at the base of flow units, and thicker developments of welded tuff in which lithic components and vitric shards are generally flattened and lens-shaped (see, for example, fiamme[6], Figure 7).

Figure 7 Silicified welded ash-flow tuff with prominent fiamme, Snowdon Volcanic Group (British Geological Survey © NERC 2014).

Under conditions of low grade hydrothermal and regional metamorphism [55] clay minerals (predominantly chlorite with sericite in more acidic compositions) have developed from original volcanic glass and igneous minerals, and these minerals are often aligned to define a cleavage comparable to that in metamudrock slates.

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[6] Fiamme are lens-shapes, usually millimetres to centimetres in size, seen on surfaces of some volcaniclastic rocks. The name *fiamme* comes from the Italian word for *flames*, describing their shape. The term is descriptive and non-genetic.

Core permeability values for the Borrowdale Volcanic Group are very low, ranging from less than 10^{-2} to 10 mD, with field values of 10^{-5} to 100 mD, including tests from faulted and fractured zones [54]. Most of the fractures intersected by the boreholes had no detectable flow.

3.1.5 Intrusive igneous rocks

Most large igneous intrusions are, broadly speaking, granitic in composition and are strong. Secondary fractures control fluid movement so that solute transport is via advection. Dependent on the extent of fracturing, these formations may provide a suitable higher strength host rock environment.

These are rocks that originated as magmas emplaced within the crust. They can form large masses (plutons) or smaller sheet-like bodies (dykes and sills). They are locally present at the surface in England, Wales and Northern Ireland, where they have intruded into either metamorphic rocks (such as slates) or sedimentary rocks, and are more widespread at depth.

Most large igneous intrusions are, broadly speaking, granitic in composition, with feldspars and quartz as the dominant primary minerals, and minor amounts of micas, amphiboles and oxide minerals. Fresh granites are very strong to extremely strong (UCS100 to >250 MPa) crystalline rocks with generally low to moderate porosity (0 to 10%, dependent on degree of alteration) and low primary permeability (10^{-8} to 1 mD). Secondary fractures control fluid movement so that field-scale permeability is typically higher (10^{-5} to 10^{5} mD) and solute transport is via advection. This permeability may be strongly anisotropic, reflecting the orientation of fracture systems and the present-day stress regime. Excavations in intrusive igneous rock may be self-supporting in deep engineered cavities, but excavation properties will be strongly controlled by local stress conditions, fracture characteristics and strength. Significant parts of some granite bodies have experienced extensive hydrothermal alteration, with replacement of feldspars and micas by clay minerals; this has a profound effect on their strength, porosity and permeability. Some alteration, such as the formation of china clay deposits (kaolinite) arose though circulation of groundwater through the cooling pluton, but in other cases the alteration may have been much later, associated with fluid flow along faults or simply deep weathering. In these cases, altered granite often exhibits a strong red colouration. Although altered granite has an enhanced porosity, much of this is in the form of micropores within feldspar grains.

The Carnmenellis Granite of south-west Cornwall provides a well characterised example of an intrusive igneous body. In common with many Phanerozoic granite plutons, the Carnmenellis Granite preserves a high thermal gradient (ca. 30 ˚C km^{-1}), hosts ore deposits that have been historically important and has been the subject of geothermal energy exploration and extensive geological characterisation [56, 57].

The Carnmenellis Granite [58] (see Figure 8) is a cupola (dome shaped), rising above the main mass of the Cornubian Batholith, continuous at depth from Dartmoor to the Isles of Scilly. It was intruded during Permian times during the latter stages of the Variscan Orogeny. The Carnmenellis Granite has a roughly circular outcrop, but is interpreted from geophysical data to be more extensive at depth. The pluton comprises a number of granite lithologies, including an outer weakly foliated megacrystic facies, typically forming the contact zone with the country rock with alkali feldspar megacrysts up to 20 mm long in a coarse-grained (3-5 mm) matrix. The central facies is also megacrystic but typically has a medium-grained (ca. 1 mm) groundmass. Other subordinate variants are fine- or coarse-grained equigranular granite and porphyritic granite with abundant white mica in the groundmass [59].

Figure 8 Example of alkali-feldspar megacrystic granite from the Cornubian Batholith (British Geological Survey © NERC 2014).

Intrusion was accompanied by thermal metamorphism of the metasedimentary slate host rocks as well as widespread emplacement of pegmatite and other veins. Ongoing hydrothermal alteration led to economic metalliferous and china clay mineralisation. Jointing is well developed in the pluton and is also often mineralised. Together, these features record a history of high to low temperature fluid-rock interaction, including interaction with ‘modern’ saline groundwaters [60]. Records of saline thermal waters (up to 45 °C) entering the excavated tin mines of Cornwall, some within the granite, show evidence of deep fracture-borne flow.

Permeabilities of Carnmenellis Granite to 300 m depth at the Troon test site were measured up to 10 mD; permeabilities of 10^{-5} to 10^{-7} mD were also reported for granite at 300 m depth at the Rosemanowes Hot Dry Rock site [61].

A global survey of data regarding permeability of crystalline rocks indicated a wide range of values (10^{-4} to 10^{3} mD), presumably representing both highly fractured and lesser fractured crystalline rocks [62].

Natural fracture networks of very high permeability (transmissivity c. 2000 Darcy m) within granite were recently reported [63]. Extremely high permeability has been found at 410 m depth in the Weardale Granite, UK, during exploratory drilling for low-enthalpy geothermal resources [64, 65] – the Eastgate Borehole was sunk down the axis of an ancient, sub-vertical hydrothermal vein structure (the Slitt Vein), proving a transmissivity in excess of 4000 Darcy m, which is one of the highest values ever measured deep within a granite intrusion. Sustained hydraulic testing showed that this transmissivity was not local to the borehole: sustained flows and steadying of drawdown suggest that this transmissivity persists along the strike of the Slitt Vein structure.

Porosity measurements from borehole cores taken from the Carnmenellis Granite, at depths of up to 1780 m, range between 0.25-1.2% [66]. However, near surface measurements from highly weathered granite are up to 16.9%. The granite is known to be well-fractured throughout, but it is in the upper 50 m, where horizontal jointing is common, that the majority of groundwater storage and flow occurs. Most water conducting fractures strike north-north-west, corresponding with orientation of the larger water inflows along major fracture zones in the mines.

Shallow groundwater in the granites tends to have a low pH (4.3 to 6.9), with low total dissolved solids contents of 54 to 371 mg/l and bicarbonate levels of 2 to 89 mg/l. Springs of saline groundwater are known to occur in tin mines at depths of over 300 m [66]. These waters are highly enriched in lithium as a result of reactions between water and the rock, and generation of radon gas from decay of uranium-bearing minerals may present a hazard.

3.1.6 Medium to high grade metamorphic rocks

Medium to high grade metamorphic rocks are crystalline. They are strong and solute transport is via advection. Some are potential HSR host rocks

These are crystalline rock units derived from sedimentary or igneous protoliths in response to changes in pressure and temperature brought about by deep burial with concomitant heating, or by proximity to an anomalous heat source, such as an igneous intrusion. These changes have driven chemical reactions among the minerals in the protolith to form more stable phases, as well as textural changes, and are influenced by any passage of fluids through the rock mass. Medium to high grade metamorphic rocks are coarser grained than low grade metamorphic rocks such as slate. They are typically strong to extremely strong rock (UCS 50 to >250 MPa) with low to moderate porosity (1 to 10%) and low permeability (10^{-7} to 1 mD). Solute transport is via advection. Secondary fractures control fluid movement and field-scale permeability is typically higher (10^{-5} to 10^{5} mD). This permeability may be strongly anisotropic because of the orientation of fracture systems. Strength is unlikely to change significantly at GDF depths. Excavations in metamorphic rock are likely to require blasting and are likely to be self-supporting in deep engineered cavities, but will be strongly dependent on local stress conditions, fracture characteristics and strength.

Metamorphic rocks that result from tectonic processes have textures that reflect new mineral growth and deformation happening together. A wide range of metamorphic rock types is possible, reflecting both the diversity of the original protoliths and the variable histories of heating and deformation that they have experienced. Most of the metamorphic rocks known at surface in England, Wales and Northern Ireland reflect metamorphism under moderate mid-crustal conditions of the greenschist or amphibolite facies, where temperatures ranged between 400 to 700˚C at pressures between 3 to 10 kbar. They include quartzite, and marble as well as a wide range of schists, but all have relatively coarse grains compared to their precursors, low porosity and any fluid transport is dominated by advection through fractures. Although some metamorphic rocks are potential HSR host rocks, others are not. Mica-rich rocks have very different physical properties from quartz-rich rocks while marbles may develop karstic weathering in the same way as limestones.

In England and Wales metamorphic rocks are known only from a limited number of exposures of Neoproterozoic rock, which tend to occur adjacent to significant fault zones. More extensive exposures are present in the north-east of Northern Ireland. As an example, the Mona Complex of Anglesey [67] comprises a number of dominantly metasedimentary units of contrasting composition. These include biotite-garnet-sillimanite schist representative of metamorphism of mudrock protoliths (precursor rocks) under high amphibolite facies conditions [68], quartzofeldspathic metasandstones with mica-rich metamudrock interlayers (Figure 9), and lenses of metamorphosed basaltic igneous rocks with a range of amphibole minerals present, representing distinctive conditions of metamorphism [69].

Figure 9 Tectonic folds in quartzofeldspathic metasandstone schist, Anglesey. (British Geological Survey © NERC 2014)

3.1.7 Sandstone

Many sandstones are porous and permeable and act as aquifers, but where porosity and permeability are low in older, well-cemented sandstones, it is possible that they could be considered as potential host rocks.

This is a commonly occurring sedimentary rock that is present throughout the geological record of England, Wales and Northern Ireland, and is considered here because it is such a widespread rock type and because it plays an important role in controlling groundwater behaviour. Many sandstones are porous and permeable and act as aquifers, but where porosity and permeability are very low in older, well-cemented sandstones it is possible that they could be considered as potential higher strength host rocks. Sandstone is deposited in terrestrial settings, including aeolian dunes and rivers, and in marine settings, including shore facies on shallow shelves or platforms and in deeper water as fans or lobes forming basin slope aprons. Sandstone consists of clasts ranging in size from 32 μm to 2 mm that are most commonly of quartz, feldspar or lithic fragments. They have a variably developed intergranular cement, most commonly of calcite or quartz that formed during diagenesis [70]. Sandstone occurs in beds of variable thickness that often preserve sedimentary structures such as grading or cross-bedding that are indicative of its mode of deposition. Strength can vary from weak to strong (UCS 1 to 50 MPa), although poorly-consolidated sand (UCS <1 MPa) may also occur at GDF depths in some formations. Sandstones have variable porosity (2-50 %) and moderate to high primary permeability (10^{-3} to 10^4 mD) with solute transport by advection. Many sandstones exhibit dual porosity, with water present both in pores throughout the rock and in discrete fractures. The fracture permeability may be dominant in more cemented horizons and the range of field-scale permeabilities is typically higher (10^{-5} to 10^5 mD) than those obtained from core-scale measurements. Sandstones often contain clay minerals and metal oxide/hydroxide phases, including iron oxide coatings on sand grains, and therefore their capacity for sorption varies inversely with the purity of the sandstone. Sandstone generally exhibits a brittle failure mode at depths less than 1 km, with a slight increase in intact strength with depth, dependent on pore pressures. Excavations in sandstone are generally machine rippable, but may require some blasting depending on factors such as bedding thickness, fracture spacing and orientation. Cavities may require support, dependent on rock mass properties and local stress conditions; the span, shape and orientation will be defined by the rock mass properties. Fractures varying on a very wide range of length-scales are often present.

For the purposes of this report, an example from the Triassic Sherwood Sandstone Group has been chosen that is relatively widespread and well described, largely because of its importance as an aquifer. However, because of its high porosity and permeability, it is unsuited as the GDF host rock. The Sherwood Sandstone was deposited in a terrestrial environment from alluvial fans, braided and meandering rivers and aeolian sand dunes. The conditions at the time were largely arid and interlayered playa mudstones and halite deposits attest to high rates of evaporation from ephemeral lakes.

The overall structure of Sherwood Sandstone Group formations is highly variable; the following example is based on the St. Bees Sandstone Formation of West Cumbria [71, 72, 73], see Figure 10. This formation comprises fluvial channel facies of 2-5 m thick units of fine- to medium-grained sandstone in lensoid bodies, commonly preserving trough cross-bedding interlayered with subordinate units of reddish mudstone up to 0.5 m thick and beds of fine- to medium-grained sandstone up to 0.5 m thick (Figure 10).

Diagenesis includes precipitation of authigenic (secondary) minerals and cements in pore spaces and fractures, including anhydrite, calcite, dolomite, haematite, barite, kaolinite and illite clays [74]. The current 3.7-27.2 % porosity in the formation is considered largely secondary and attributed to dissolution of carbonate by modern groundwaters [72, 75]. Permeabilities measured on core samples and in boreholes range from below 10^{-2} up to 10^3 mD [76, 77]. These values are however several orders of magnitude less than field values derived from pumping tests.

The formation has a complex network of discontinuities comprising gently and steeply-dipping fractures, some of which may be sediment-filled, closely spaced joints and steeply-dipping faults, some of which preserve fault breccias [60, 78].

Salinity of groundwater in the Triassic Sherwood Sandstone varies widely depending on local structural and geological conditions [79, 80]. Remarkably fresh groundwater has been observed at depths to 600 m in the confined Sherwood Sandstone of the East Midlands, and this has been shown to be >10,000 years old [81]. In the Cheshire Basin and Merseyside, saline groundwater exists at depths of typically 200 m, but can be shallower depending on groundwater flow paths, which are themselves influenced by faulting ([82, 83]). Groundwater is anoxic in deep flow paths. Groundwater from the Sherwood Sandstone can possess high concentrations of dissolved sulphate and bacterially-mediated sulphate reduction has been observed in groundwater at depth at some locations.

Figure 10 St Bees Sandstone Formation showing sheet sandstones near the base of the quarry overlain by channelised sandstones (British Geological Survey © NERC 2014).

3.1.8 Low grade metasandstone

Metasandstone has low to moderate porosity, low to moderate primary permeability and solute transport is largely by advection. Metasandstones are potential HSR host rocks, but in practice seldom form sufficiently large bodies to be of interest.

This class comprises beds and units of sandstone that have undergone an extensive history of diagenetic cementation and recrystallisation during very low grade metamorphism. It is typically medium strong to extremely strong (UCS 25 to >250 MPa) and likely to fail by brittle fracture at GDF depths. Metasandstone has low to moderate porosity (<15%), low to moderate primary permeability (10^{-4} to 100 mD) and solute transport is largely by advection. Field scale permeability is generally higher and influenced by the presence of fractures (10^{-2} to 10 mD). Excavations may require blasting and engineered cavities at depth may require support, depending on rock-mass quality and degree of fracturing.

As in the metamudstone slate class, most of the rocks considered to be metasandstone are of Palaeozoic age and have been subject to Silurian (Caledonian) or Carboniferous (Variscan) tectonism. Metasandstones are potential HSR host rocks, but in practice seldom form sufficiently large bodies to be of interest. In general, metasandstone formations are turbidite sequences in which sandstone and mudrock are thinly interbedded.

3.1.9 Limestone, including chalk

Limestone is dominated by carbonate minerals. Solute transport in limestones is via advection. Low porosity, muddy limestone units with few fractures are potential HSR host rocks if the beds are thick and continuous enough, and karst is not developed, but most UK limestones are unlikely to meet these criteria.

This rock type is dominated by carbonate minerals (normally calcite or dolomite, but sometimes aragonite or iron-bearing carbonates) and primarily derived from biogenic sources (biogenically mediated precipitates and fossils). They comprise a number of end member lithologies that preserve highly variable, scale dependent strength properties ranging from weak to very strong (UCS 5 to 250 MPa) with highly variable porosity (0.1 to 50 %), primary permeability (10^{-7} to 10^{3} mD) and field-scale permeability (10^{-1} to 10^{6} mD) [72]. Limestones include formations ranging from the Cretaceous Chalk, which is weak, highly porous and permeable where fractured, to Carboniferous Limestone, which includes significant units that are very strong and have very low porosity and intergranular permeability, with groundwater flowing through solutionally-enlarged fractures (secondary permeability). Solute transport in limestones is via advection, through the solutionally-enlarged fracture network, with some diffusion through the primary (matrix) porosity where present, such as in the Cretaceous Chalk. The strength and stiffness of limestone units may change with depth, and both brittle and ductile deformation behaviour is possible at GDF depths. Excavations may require blasting, depending on local intact strength and rock mass characteristics. Deep engineered cavities in limestone may or may not require structural support, depending on rock mass quality properties and stress conditions. Low porosity, muddy limestone units are potential HSR host rocks if the beds are thick enough and karst is not developed, but most UK limestones are unlikely to be suitable. As an example of limestone, Chalk underlies much of the south and east of England. It comprises a soft, very pure white limestone formed from the calcitic skeletal components of planktonic marine algae that have accumulated on the sea-bed [84], Figure 11 shows a typical UK formation. Because of the planktonic nature of the original algae, chalk ooze is deposited across a variety of marine settings and water depths.

Figure 11 Chalk cliffs at Flamborough Head (British Geological Survey © NERC 2014).

The main subgroup level stratigraphic divisions within the Chalk reflect a higher proportion of clay minerals in the Grey Chalk versus a near pure calcium carbonate composition in the White Chalk. Thin beds of bentonitic calcareous marl form prominent marker horizons within the Chalk succession and are thought to be of volcanic origin. During diagenesis, nodular chalk hardgrounds formed locally in response to lithification at the sea-floor. Chalk is locally rhythmically layered with nodular silica (flint). Fractures are widely developed in Chalk [85], and the frequency and style of these is in part stratigraphically-controlled. They are best developed in the shallow subsurface and become less common below 60-100 m depth. However, significant water yielding fractures have been identified at depths of over 300 m in the Wessex Basin. Dissolution features (karst) are widespread in the shallow subsurface (to around 40 m) and may form pipes that are often sediment filled. Dissolution is known to enhance permeability, although some internal features such as marl and flint beds locally act as low permeability aquicludes and may partition groundwater flow [86]. The Chalk forms an important dual porosity aquifer. Small pore throat diameters inhibit gravity drainage so that primary permeability is very low (1 mD [72, 87]) and water movement is dominated by the secondary permeability, although solute transport takes place via both. Field-scale permeabilities obtained from pumping tests are of the order of 10^3-10^4 mD (assuming a contributing saturated thickness of 60 m; [72]).

Other limestone formations in England, Wales and Northern Ireland, such as Carboniferous or Jurassic limestone, were typically deposited in shallow marine settings near shore, such as lagoons and platforms that were relatively starved of terrigenous clastic input. These successions are typically thinner and more heterogeneous. They contain over 50% carbonate minerals, principally calcite and dolomite, and typically formed *in-situ* from the accumulation of carbonate in the skeletons of reef-building organisms or by the trapping and binding of sediments in microbial mats, as well as re-sedimented deposits [88]. The style of the deposits is very variable and includes massive reef structures through to very finely laminated beds produced by algae or microbes. Bedding can also be cyclical, with regular alternations of limestone and marl, or limestone and cherts, reflecting changes in sea-level or periodic storm events. They are affected by diagenetic dissolution, and replacement of aragonite and crystallisation of dolomite by the partial or complete replacement of calcium within the carbonate rock by magnesium. This process of replacement can occur due to evaporitic conditions during emergence and pedogenesis, or during shallow to deep burial diagenesis. A feature of the Carboniferous Limestone is widespread karstification. Features include small and large scale sub-surface conduits ranging from millimetre scale to large caves. Whilst most karst occurs near the surface, the deepest caves in the UK are up to approximately 300 m deep and systems between 100 and 200 m are not uncommon.

The matrix of the Carboniferous Limestone is essentially impermeable, and groundwater is contained within, and flows through, fractures and caves that can transport large volumes of water. The quality of shallow water from the Carboniferous Limestone tends to be of calcium-bicarbonate type. The karstic nature of Carboniferous Limestone aquifers leads to the potential for rapid and unpredictable groundwater movement connecting deep groundwater with shallow systems.

3.2 Rock structure and rock heterogeneity

Faults, fractures, folds and other structures affect the 3D geometry of the geological environment, as well as the hydrogeological properties of both the host rock and the cover rocks. Furthermore, host rock and cover rocks vary spatially (both laterally and vertically). Discontinuities and spatial variability in all rock types can occur on a range of length scales.

The design and construction of the GDF and the evaluation of the likely performance of its geological barrier are dependent on an understanding of the distribution of rocks with specific properties at a site and of the nature of the discontinuities that separate different rock bodies. In part, variations in rock properties reflect original heterogeneity in the rocks, but in part they arise as a result of processes that have affected the rocks after they formed, such as faulting. Most rock properties are heterogeneous and heterogeneity generally occurs across a very wide range of length scales. This section considers both primary features of rocks that give rise to heterogeneities, and structures formed subsequently by deformation.

The heterogeneity of the fluid flow properties of the rocks has implications for assessing the groundwater pathway and the consequences of gas generated within the GDF. A high degree of heterogeneity leads to uncertainty because it is not possible to determine the detailed irregular variation of the rock properties in a region of interest, since any site characterisation will only involve a finite number of observations. Heterogeneity also leads to dispersion of any plume of chemical species being transported by moving groundwater, because the groundwater velocity and solute retention would vary over the plume as a result of the heterogeneity in the rock properties. Hence, parts of the plume in different locations would move at different velocities, which would tend to lead to the plume spreading out. It is therefore important to take heterogeneity into account, and deal with it appropriately, in the characterisation of a potential site for the GDF, the design of the GDF and the assessment of the performance of the GDF.

In a recent report to RWM [89] an overview of techniques for representing heterogeneity is presented, and current approaches to dealing with heterogeneity in the oil industry, water industry and radioactive waste disposal programmes in other countries are discussed. Fundamentally, there are two approaches for treating heterogeneity, although in practice, all methods may have aspects of both approaches. The first approach is to determine suitable homogeneous (that is, not spatially varying) effective (or equivalent) properties that represent the overall or average behaviour of a volume of rock of interest. This approach may be appropriate for properties whose variability is relatively small and normally-distributed, but is not always applicable to geological variables. For example permeability varies by orders of magnitude even within reasonably uniform lithologies, and so regional fluid flow may be dictated by quite minor lithologies with outlier properties. The second approach is to try to represent the variation for each spatially varying property of interest. This second category can be divided into deterministic, stochastic and evolutionary approaches. The major variability is captured by the recognition of different rock types with different properties (that is, by a deterministic approach), but it is important also to capture the variability within the mapped units of those rock types, and here a stochastic approach will be appropriate.

The UK is tectonically stable and does not contain major active fault zones (see Section 4 for further discussion). However faults, fractures or folds formed in the past occur in almost all kinds of geological environment. These may provide limits to the rock volumes available for siting the GDF and may also form conduits or barriers to groundwater flow, depending upon their characteristics.

3.2.1 Primary heterogeneity in igneous rocks

Higher strength rocks that are intrusive igneous bodies may show compositional and textural variations related to the original history of magma emplacement, while higher strength rocks of extrusive origin may show variations related to the history and characteristics of volcanic eruptions (for example, the thickness and spatial distributions of distinct pyroclastic layers, and the presence of magmatic rocks as well as pyroclastic deposits). Igneous rock bodies can vary greatly in size, and the presence of a suitable rock volume is a prerequisite for consideration of an igneous rock as a potential host.

Successive magma pulses in an intrusive body may give rise to visually distinct rocks, but they are unlikely to have significantly different properties. Some intrusions contain xenoliths of metamorphic rock, especially near their margins, but, unless these are of marble, it is again unlikely that the properties will be greatly different from those of the igneous rock.

When first formed, lava flows and shallow intrusive rocks may have very different properties from any associated pyroclastic deposits, with the magmatic rocks typically of much lower porosity and permeability. Many extrusive rocks undergo hydrothermal alteration shortly after their eruption, and this may tend to reduce the difference in properties between pyroclastic and magmatic rocks. However where there has been subsequent regional metamorphism, the differences are often reduced further.

3.2.2 Primary heterogeneity in sedimentary rocks

Sedimentary formations are by their nature stratified and laterally continuous, but the individual beds within them are more likely to be impersistent at the scale of the area that will need to be considered during siting of the GDF. Their lithological characteristics are determined to a large extent by their composition, environment of deposition and subsequent diagenetic history. Lateral gradations between different original depositional environments will be expressed in lateral variations in lithological characteristics that are present (for example, grain size, porosity, nature of cements). Lithological characteristics may vary sharply or gradually in the vertical direction. Similarly, changes in thickness tend to be gradual unless they are associated with faulting that occurred during sedimentation or arise from unconformities within the sedimentary sequence.

Sediments deposited in quiescent marine environments are likely to vary in lithology and thickness only gradually, even over many kilometres, whereas sediments deposited in shallow marine to terrestrial settings are much more likely to have a complex sedimentary architecture with, for example, beds truncated by local erosional features and linear deposits of channel-fill deposits. The impact that sedimentary architecture may have on fluid movement in hydrocarbon reservoirs has been studied extensively and is relevant to possible return pathways of deep groundwater to the surface. Local heterogeneity in evaporite sequences is also common and may be particularly significant because where discontinuous beds of sediments that contain pore water are entirely surrounded by rock salt, the pore water may be overpressured. In addition to horizontal beds, some sedimentary sequences may also contain vertical sheets or pipes of sandstone that cut across beds. Such neptunian dykes are significant because they may provide a permeable connection between aquifers that would otherwise be separated by an impermeable lithology.

3.2.3 Secondary heterogeneity: joints and faults

There are a range of features that involve the presence of fractures developed in pre-existing higher strength rocks, irrespective of their ultimate origin. Cracks that do not involve displacement across them are known as joints. In extrusive igneous rocks, joints may include cooling cracks formed at the outset, but in most rock types, joints form in orientations that reflect regional stresses in the crust; most are near-vertical, with horizontal joints linked to uplift and unroofing and mainly present near the surface. Joints are important for transmission of groundwater at shallow levels, but even at depths of a few hundred metres their transmissivity is often greatly reduced and typically only joints that are oriented parallel to the maximum horizontal stress will be transmissive [80].

Faults and fault zones (including shear zones) are examples of discontinuities across which rocks have been displaced, sometimes by many kilometres. Many of the major faults affecting sedimentary sequences were active during sedimentation, and influence formation thickness. Sequences of the same age often continue across the fault, but are much thicker on the downthrown side. These types of extensional faults commonly extend into the underlying basement rocks, where they may become less steeply inclined. Large faults often have a long history of movement and this may result in a wide range of rock types being juxtaposed. In addition to normal faults formed by crustal extension and the development of sedimentary basins, thrust faults are important in some parts of the country and steep strike-slip faults may also be present. Where faults cut igneous and metamorphic (crystalline) rocks, their displacement may be hard to determine, but even in homogeneous crystalline rocks large faults are typically accompanied by damage zones in which an array of smaller faults, cracks and microcracks are present and the rock has often been subject to significant hydrothermal alteration.

Faults may juxtapose formations with very different properties and the impact that they have on regional groundwater behaviour will depend on the rocks affected and the style of faulting. Some may act as hydrogeological barriers and others as transmissive features, and understanding and predicting this has been a major objective for the conventional hydrocarbon industry. Typical sedimentary sequences include a mix of aquifers and aquicludes (a layer of rock through which ground water cannot flow), and where fault displacement juxtaposes aquifers against aquifers, fluid can often move across the fault within aquifer beds, while aquifers that are faulted against aquicludes may become isolated from the surrounding fluid regime, or compartmentalised,. Where faults have a significant damage zone in their core this may act as a zone of enhanced permeability, especially where the movement has been extensional in nature. However, if the damage zone has been sealed by precipitation of minerals such as halite or involves smearing of clay minerals, it may form an impermeable barrier between the rocks on either side, even if they are aquifers. Detailed investigations are required to establish whether specific faults are likely to be barriers or conduits for fluid flow [90]. In sedimentary sequences, fluid flow is possible through both transmissive faults and aquifers, but in low permeability crystalline rocks (including low grade metamorphic rocks), where flow is dominated by faults and other fractures, the extent to which flow is possible depends not just on the properties of individual fractures but also on the degree to which they are interconnected.

Layered rock sequences may also be folded on a range of length scales. As for faulting, some of these structures may be syn-sedimentary but persistent fold structures with a consistent orientation are of tectonic origin. Folding, and the steepening of dips in general, has significance for the design of the GDF since it may facilitate fluid flow from deeper to shallower levels along steep fold limbs. Folding during metamorphism is accompanied by recrystallization of the entire rock body and if this is sufficiently intense the rock properties will become more uniform, reducing the likelihood that differential fluid flow can take place along original layers. Where folded rocks retain markedly different strength or permeability during folding, as in unmetamorphosed sedimentary sequences, and where individual layers develop fractures or spaced cleavage during folding, folds are most likely to influence groundwater flow patterns.

As with faulting, folding introduces complexity into the geology of a region. Folding patterns may be regular and predictable, but the greater the lithological contrasts between the folded layers, the more irregular the fold pattern is likely to be. Figure 12 [91] shows an example of a geologically-complex succession, the Cwmystwyth Grits Group of the Lower Palaeozoic Welsh Basin (for example, [92]), which illustrates a number of points about rock structure. Tectonic shortening of the multi-layer successions has given rise to intense folding on a kilometre- to metre-scale, so that beds are typically moderately-inclined to sub-vertical. Within the Cwmystwyth Grits Group, typical turbidite units comprise graded beds of metasandstone ranging from 2 cm to 30 cm in thickness, passing up into finer-grained rocks. In parts, the metasandstones can reach around 2 m in thickness. Individual graded turbidite units are often overlain by thin, cm-scale, laminated hemipelagite mudstone, although this may have been eroded by deposition of the subsequent unit. Stacking of successive turbidity flow deposits gives rise to a multilayer appearance of the rocks on a cm-to-metre-scale, in which the proportion of metasandstone may vary between around 10% and 60%. During regional deformation and very low grade metamorphism, the turbidite units have experienced low grade metamorphism. Original sandstones developed a spaced cleavage and quartz has remobilised and recrystallized, reducing the porosity. Mudstone portions of the unit have been compacted and recrystallized and now have minimal porosity and aligned platy minerals giving rise to a slaty cleavage. The intergranular permeability of the Cwmystwyth Grits is minimal but it can be seen from Figure 12 that the deformation has generated many fractures across the metasandstone layers, while tight fold limbs have become faults. As a result, water movement and storage are controlled by the degree of fracturing and fracture connectivity and these are heterogeneous at all scales [93]. Cleavage planes typically have centimetre-spacing and in many beds pressure solution in cleavage planes has given rise to irregular apertures and voids. Propagation of other fractures, including veins and joints is also common, and tectonic shortening of the multi-layer successions typically gives rise to intense folding on a kilometre- to metre-scale, so that beds are typically moderately-inclined to sub-vertical.

The Cwmystwyth Grits Group is evidently unsuited as the GDF host rock (c.f. Section 2.3.2) but does illustrate an extreme but quite common example of heterogeneous rock type and complex rock structure.

Figure 12 Folded succession of interbedded very low grade metasandstone and metamudstone from the Cardigan Bay coast (British Geological Survey © NERC 2014).

3.3 Groundwater

Hydrogeological and hydrochemical characteristics of the geological environment are important.

This section describes how key hydrogeological and hydrochemical characteristics of the geological environment, such as permeability and groundwater chemistry, contribute to the GDF's ability to isolate and contain radionuclides over long timescales.

3.3.1 Groundwater flow

Natural groundwater movement will affect how dissolved chemical species could migrate in solution. Such species could return to the surface environment on very different timescales. Understanding how groundwater movement has occurred and is currently occurring at a potential GDF site, is therefore important, as this informs our understanding of how future groundwater movement could occur.

Groundwater flow is induced when there is a difference in hydraulic head across a permeable rock body. This may arise, for example, in response to differences in temperature or water composition, or to topographic gradients; however, additional factors may be important at GDF depths. Flow is assumed to follow Darcy's Law, which relates fluid flux to the hydraulic gradient, the permeability of the rock body and the properties of the specific fluid present. Low groundwater flow rates, which are likely to inhibit transport of radionuclides from the GDF, require low host rock permeability and low hydraulic gradients.

Hydraulic gradient is the difference in hydraulic head per unit distance of separation. The direction of groundwater flow is usually determined by the direction in which the hydraulic gradient is steepest, unless permeability is strongly anisotropic. As a result, hydraulic gradients control the regional- to local-scale geometry of the groundwater flow system.

Intrinsic permeability is a measure of the ease with which a rock allows flow and is controlled by the size and proportion of voids (porosity) in the rock and the nature and degree to which these are interconnected. Hydraulic conductivity, a related term, describes the conductivity of a rock to pure water, and takes account of the properties of both the porous medium (through the intrinsic permeability) and the fluid (through density and dynamic viscosity), which in turn are affected by other parameters such as temperature and salinity.

Primary permeability is permeability that is provided by connected intergranular spaces, whilst secondary permeability constitutes that provided by fractures. Many rock types exhibit dual porosity, that is, a combination of both primary and secondary permeability, although one of these often dominates.

The term ‘fracture’ is used here to refer to discontinuities across which the rock integrity has been disrupted and includes commonly observed geological features including joints and faults [94]. Fractures can be enlarged by dissolution and may be open in the near surface as a result of stress relief, but tight at depth. Permeability may be modified significantly by the growth or dissolution of minerals in pores or fractures.

The overall permeability of a higher strength host rock body will largely be determined by the frequency, inter-connectivity and transmissivity of discontinuities. This is because higher strength host rocks have very low primary permeability and any groundwater flow that occurs through them is dominantly through discontinuities; the permeability of the rock matrix would be very low and any water or solute transport in the rock matrix would be dominated by diffusion. It has been proposed (for example, [95, 96]) that the contribution of diffusion into the rock matrix may be significant in terms of overall solute transport. The effectiveness of rock matrix diffusion, as opposed to advection – dispersion through micro-cracks parallel to a main fracture, is subject to ongoing discussion, and is discussed in detail in [5] (see also Task 372, [11]).

A higher strength host rock may be subdivided or compartmentalised into multiple hydrogeological domains, perhaps delineated by larger faults or shear zones, and/or on the basis of lithological variations. If these domains are not especially well connected there may be significant differences in groundwater pressure between adjacent zones, resulting in potentially large pressure differences being present across impermeable boundary features such as faults or shear zones. As a result, the hydrogeology of higher strength rocks may be complex.

Higher and lower permeability formations are defined on the basis of their hydrogeological properties. Higher permeability formations are able to support sufficient flow for advective mass transport if groundwater pressure gradients are sufficiently large. Flow may be through the matrix, through fractures or through a combination of the two. Some higher permeability sedimentary rock formations may be limestones or highly cemented siliciclastic rocks, through which groundwater will flow dominantly via fractures. Low permeability formations are unable to support sufficient flow for advective mass transport, and thus provide a diffusion-dominated barrier.

The permeability of a higher or lower permeability formation may be anisotropic (usually vertical permeability is less than horizontal permeability) as a result of the inter-bedding of lithologies with different hydrogeological properties or due to the sedimentary processes that resulted in the preferential orientation of minerals. This layering and anisotropy may promote sub-horizontal flow and vertical stratification of the hydrogeological system. Specifically, the presence of a laterally persistent low permeability bed is likely to prevent movement of groundwater between overlying more permeable units and those beneath. The deep groundwater in this situation is likely to be old and slow moving. Additionally, where highly permeable rocks overlie much less permeable ones (as at some basal unconformities) the much higher flow through the overlying rocks is also likely to result in effective separation of the above and below groundwater systems.

Halite (evaporite) and halite-dominated units have a permeability that is sufficiently low to ensure that there would be no meaningful groundwater flow and any mass transport would be by diffusion.

The presence of faults can have a significant impact on groundwater flow, but, as noted in Section 3.2, the effects may be difficult to predict. In layered sedimentary sequences, displacement of faults may result in rocks of very different permeabilities being juxtaposed across the fault plane. This will constrain flow in aquifers that are juxtaposed against impermeable beds, but may also allow fluid to flow from one aquifer horizon to another across a fault plane. Additionally, the hydraulic properties of the fault itself may be very different from those of the rocks on either side. In some situations, the fault is accompanied by a damage zone in which multiple small fractures have the potential to provide additional permeability. Whether this effect is significant depends firstly on the present-day stress orientation, which will serve to prevent fractures in specific orientations from opening and permitting flow, and secondly on whether secondary mineral precipitates have infilled the fractures themselves [90, 97, 98].

At shallow depths, hydraulic gradients reflect variations in the elevation of the water table and in some areas also horizontal variations in groundwater density, for example, due to variations in salinity. In many cases, as a result of recharge, the water table is close to the ground surface. However in some cases, such as regions of high elevation, or where the near-surface rocks have a high permeability, the water table may be significantly below than the ground surface. Low permeability layers in the superficial deposits may result in the development of perched water bodies and partially saturated conditions in the underlying unit. The topographic gradients local to a site do not necessarily determine the flow at depth at that site, but rather flow at depth reflects the average gradient over some distance, which depends on the anisotropy of the effective hydraulic conductivity of the overlying rock. Current flow at depth might be out of equilibrium with the shallow hydrology at a site. For example, past climate conditions experienced by a site may still influence hydraulic heads at depth in low permeability rocks.

Groundwater flow at depth can be out of equilibrium with current conditions at the ground surface. There are two main processes that can lead to this situation:

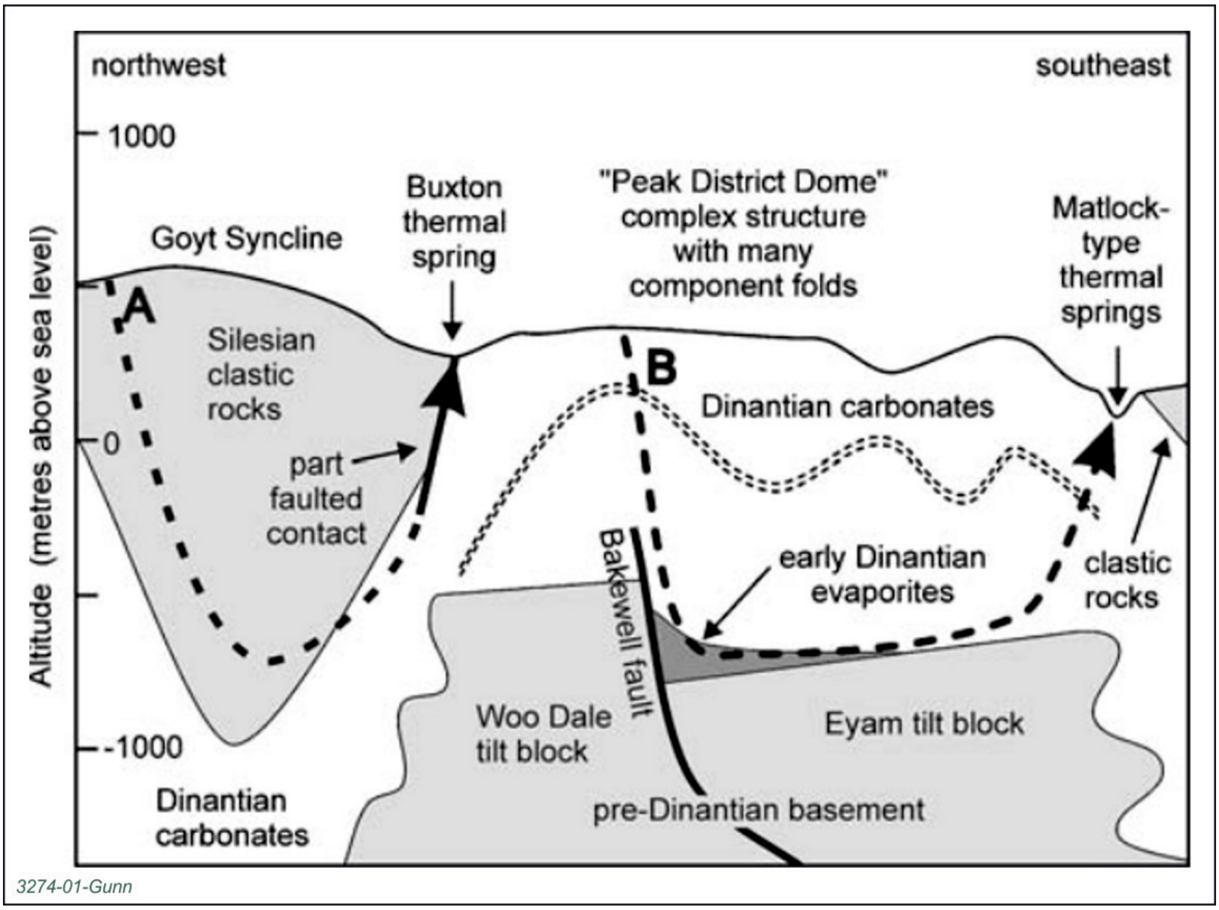
- The first process is the movement of salinity. Under past conditions, the groundwater flow regime could have been different, for example as a result of high water pressures beneath an ice sheet, a different recharge regime (for example, when permafrost is preventing recharge or climate was different) or subsequent erosion or uplift. The distribution of salinity could have evolved to a distribution that is not in equilibrium with current surface conditions (for example current recharge conditions). The distribution of salinity will now be slowly moving towards equilibrium, but in a low-permeability rock, with low flows, this may take a long time (and indeed the salinity distribution may never reach equilibrium, because the conditions may change again before this occurs)
- The second process is that high water pressures may have developed in some rock formations in the past, for example as a result of high water pressure beneath an ice sheet or as a result of cover rocks, which have now been eroded, formerly being present. In a low permeability rock it may take a long time for these high pressures to dissipate.

3.3.2 Anomalous deep groundwater flow

In some geological settings, groundwater rises to the surface from considerable depths; these waters are thermally and/or chemically distinctive. Such flows would indicate a hydrogeological environment unsuitable for hosting the GDF.

In some geological settings, groundwater rises to the surface from considerable depths, often in excess of 1 km, and such behaviour is clearly significant for the siting of the GDF. These waters are thermally and/or chemically distinctive; they form mineral springs or warm springs. Most commonly, such flows are associated with the existence of karst-weathered limestones; an example of such a flow system is illustrated in Figure 13 (from [99]). There are also examples of deep flows associated with major faults and fracture systems, and an example is the deep-flow system encountered at depth by drilling at the Eastgate borehole into the Weardale granite [64]. Reference [100] presents several examples of anomalously-saline groundwater flow in the GDF depth range.

Figure 13 **Composite conceptual model of major geological components and deep thermal groundwater flow between the Goyt syncline in the west and the Derwent valley in the east. All topographical and geological relationships are greatly simplified. The nature and position of the Bakewell Fault and related basement bocks are speculative [101]. Vertical exaggeration about x20. Figure from [99], with grateful acknowledgement.**



3.3.3 Chemical environment

Groundwater chemistry will affect the transport of any dissolved chemical species. Understanding how the chemical environment of the GDF site (factors such as pH, Eh, groundwater salinity and the presence of dissolved sulphide) has evolved and is currently evolving, on geological timescales, is therefore important as this informs an understanding of how future changes to the chemical environment could occur.

The integrity of the GDF is also governed by the ambient chemistry of groundwater in the host rock and its interaction with the materials used in the waste container and other engineered barriers. In particular, groundwater salinity and redox state (Eh) are important factors in determining, for example, the rate of corrosion that could affect waste containers. The chemistry of deep groundwater is complex and in some respects is specific to the geological environment, being dependent on the regional geological and hydrogeological environment, as well as the history of groundwater movement. For slow-moving groundwater, the mineralogy of the enclosing rocks is also very significant. In some respects, slow-moving groundwater is a saturated solution of the rocks that enclose it, albeit affected by mineral solubility. For example Eh is sensitive to mineralogy, with groundwater able to participate in redox reactions with host minerals containing iron or sulphur in particular. However the total dissolved load of many groundwaters is dominated by chloride salts and chloride is an example of a very conservative element, mainly present in the pore waters with very little available from the enclosing rocks, unless they are evaporites. Very deep groundwaters are often dense brines, while in coastal regions, seawater incursions are common. These waters can only very slowly change their salinity as they move, although other aspects of their chemistry, such as the relative proportions of metal cations or concentrations of sulphate, may change in response to reactions with rocks and, potentially, with the materials of the EBS.

In some permeable aquifers (for example, sandstone), groundwater can be fresh to depths of over 200 m and in places up to 400 m. At greater depths and in less permeable rock types groundwater is normally saline. In general terms, groundwater at depths of 200 m to 1000 m is also anoxic. Absolute concentrations of solutes vary widely (ranging from brackish to brine), but salinity of deep groundwater is usually dominated by Na-Cl solutions, in contrast to the Ca – HCO_3 waters that predominate in aquifers. Some saline deep groundwater may be relatively enriched in Ca and Mg; high SO_4 concentrations are also a feature of some groundwaters, depending on the mineralogy of host rocks. Dissolved sulphide may be present under more strongly reducing conditions, consistent with microbially-mediated sulphate reduction. The presence of salinity in groundwater, or groundwater with high concentrations of sulphate and/or dissolved sulphide, can result in higher corrosion rates of metals present in waste containers, but also demonstrates that the deep groundwaters are isolated from shallow groundwater systems that are accessed by human activity.

Different instances of a particular geological environment may contain groundwater with widely differing groundwater compositions. These compositions will depend upon the particular geographical location of the environment and its history, particularly its climatic history and the extent to which it has been impacted by sea level change. These factors will determine the different sources of groundwater and solutes.

Several different geochemical characteristics can be used individually or in combination to classify groundwaters. For example, a combination of salinity levels, major cation and anion ratios, redox states and pH may all be used when classifying groundwater. However, within any classification scheme, water compositions of a given general type will show considerable variability. Any groundwater will contain a mixture of solutes from different sources, while mixtures of two or more groundwaters of different composition will have intermediate compositions that reflect the mixing proportions.

3.3.4 Solute transport and retardation

Solutes are transported in groundwater by advection and diffusion. Since diffusion is a slow process, the rate of the migration of chemical species will be very much lower in rocks that are of very low permeability than in rocks where advective transport occurs. Transport of radionuclides through host rocks depends on the degree of retardation by adsorption processes.

Solute transport through host rocks occurs via advection or diffusion. Advection, the process by which solutes are transported by bulk motion of flowing groundwater, is controlled by the parameters governing groundwater flow discussed in the previous section. Diffusion, the process by which solutes move under the influence of their kinetic activity in the direction of the chemical potential gradient, occurs in the absence of any bulk hydraulic movement of the fluid. At very low groundwater velocities, mechanical dispersion becomes negligible relative to diffusion. Where the permeability is less than 0.01 mD, distinguishing between advection and diffusion becomes difficult [102, 103]. Diffusion is the dominant solute transport mechanism in unfractured clays and mudstones, where transport by moving groundwater is negligible. In many other rocks, transport occurs via a combination of advection and diffusion. Since diffusion is a slow process the rate of radionuclide migration will be very much lower where diffusion-limited than in rocks where advective transport dominates.

Transport of radionuclides through host rocks is also controlled by the degree of retardation by adsorption. Retardation is the slowing down of solute species as they move through a material because they are retained on mineral surfaces as they move past. It is a function of the host minerals and their surface properties, and also of the hydrochemical environment, but is most effective in rocks containing sorbents such as clays, metal oxides/hydroxides, phosphates or organic matter. Adsorption capacity is also dependent on groundwater salinity, redox status and pH (see Behaviour of Radionuclides and Non-radiological Species in the Groundwater Status Report [5]).

Solute transport by advection can be affected by ‘apparent retardation’ of the solutes due to diffusional exchange with microporosity. This is best documented in the Chalk, but could equally apply to, for example, fractured mudstones with high inter-granular porosity. In reality, many systems can be conceived as being a hybrid between purely advective and diffusion-dominated transport, and models exist that allow quantification of such hybrid, dual-porosity transport phenomena (see, for example, [104]).

3.4 Summary

In Section 3, the properties of geological materials in England, Wales and Northern Ireland have been described and illustrated with reference example formations from the geological record. The geological properties of these geological materials are summarised in Table 1.

Table 1 Summary properties of significant geological rock types in England, Wales and Northern Ireland.

Class	Lithology	Porosity (%)	Primary permeability (mD)	Field-scale permeability (mD)	Solute transport mechanism	Unconfined Compressive Strength (MPa)
Evaporite	Thin to thick units of evaporite minerals with beds of mudstone, marl or limestone	low (<0.1)	low (10^{-6} to 10^{-5})	low (<10^{-3} to 10^{4})	Diffusion	Weak (5 to 25)
Mudrocks: Clays	Units of plastic claystone	high (40-70)	low (10^{-5} to 1)	low (10^{-5} to 1)	Diffusion	Very Weak to Weak (1.15 to 25)
Mudrocks: Mudstones	Units of weakly lithified mudstone	variable (1 to 40)	variable (10^{-4} to 100)	low ($10^{-5}$to 1)	Diffusion	Weak to Medium Strong (5 to 50)
Metamudstone shales and slates	Mudstone lithologies with penetrative slaty cleavage	low (<5)	low (10^{-8} to 10^{-3})	low (10^{-4} to 10^{-3})	Diffusion	Strong to Very Strong (50 to 250)
Extrusive igneous rocks	Units of erupted volcanic debris	variable (0 to 50)	low (10^{-5} to 10)	variable (10^{-1} to 10^{6})	Advection	Strong to Extremely Strong (50 to >250)
Intrusive igneous rock	Plutons, dykes and sills of crystalline rock	low to moderate (0 to 10)	low (10^{-8} to 1)	variable (10^{-5} to 10^{5})	Advection	Very Strong to Extremely Strong (100 to >250)
Medium to high grade metamorphic rock	Units of schists and related rock types	Low to moderate (0 to 10)	low (10^{-7} to 1)	variable (10^{-5} to 10^{5})	Advection	Strong to Extremely Strong (50 to >250)
Sandstone	Units of lithified sandstone	variable (2 to 50)	variable (10^{-3} to 10^{4})	variable (10^{-5} to 10^{5})	Advection	Weak to Extremely Strong (1 to >250)
Low grade metasandstone	Re-crystallised sandstone lithologies with a spaced cleavage	low to moderate (<15)	variable (10^{-4} to 100)	low to moderate (10^{-2} to 10)	Advection	Medium Strong to Extremely Strong (25 to >250)
Limestone including chalk	Units of calcium or calcium-magnesium carbonate minerals	variable (0 to 50)	variable (10^{-7} to 10^{3})	variable (10^{-1} to 10^{6})	Advection/ Diffusion	Weak to Very Strong (5 to 250)

Porosity and permeability values after: [40, 47, 72, 62, 105, 106, 107, 108, 109, 110, 111, 112].

4 Potential implications of present and future large-scale natural processes for a UK GDF

This section discusses how the geosphere could be affected by large-scale natural processes relevant to the UK over the next one million years, and the potential significance of these to the GDF. Such processes include tectonism, including earthquakes; subsidence, uplift and erosion; and permafrost development and periods of glaciation.

The GDF siting process will take into account large-scale Earth and climate-related processes that will affect the subsurface environment. Until specific sites have been identified as potential locations to host the GDF, it is not appropriate to undertake a detailed assessment of many of the future changes noted in the present section. However, further research at a generic (non site-specific) level into the key processes noted herein has been identified in RWM's Science and Technology Plan [11] (Tasks 331 to 350).

The Earth is a dynamic system in which complex, interacting processes evolve over time. To ensure geological stability of the GDF over the time period during which the wastes remain hazardous (up to 1 million years), it is necessary to be able to rule out or forecast the geological changes that are likely to impact on the post-closure performance of the GDF. This section provides a summary description of the current understanding of aspects of the Earth's natural evolution relevant to the geological disposal of radioactive waste and an account of the impact that these may have on the post-closure safety functions of a UK GDF.

International radioactive waste disposal programmes have made a significant effort to evaluate long-term natural processes that may affect the evolution of the geosphere with respect to their regions. These have highlighted the following processes as being significant to the GDF sited in northern Europe [113, 114, 115]:

- plate tectonics and the impact of seismicity and volcanism
- uplift, subsidence and erosion
- climate evolution, in particular the impact of glaciation, permafrost and sea-level change.

The work described in this section has been the subject of significant efforts by RWM in recent years, and so is presented in more detail than some of the other more site-specific geological topics discussed in this report.

4.1 Plate tectonics and the impact of seismicity and volcanism

Plate tectonics and the impact of seismicity have the potential to affect the GDF. Volcanism, however, is not relevant in the UK context over the next one million years.

4.1.1 What is plate tectonics?

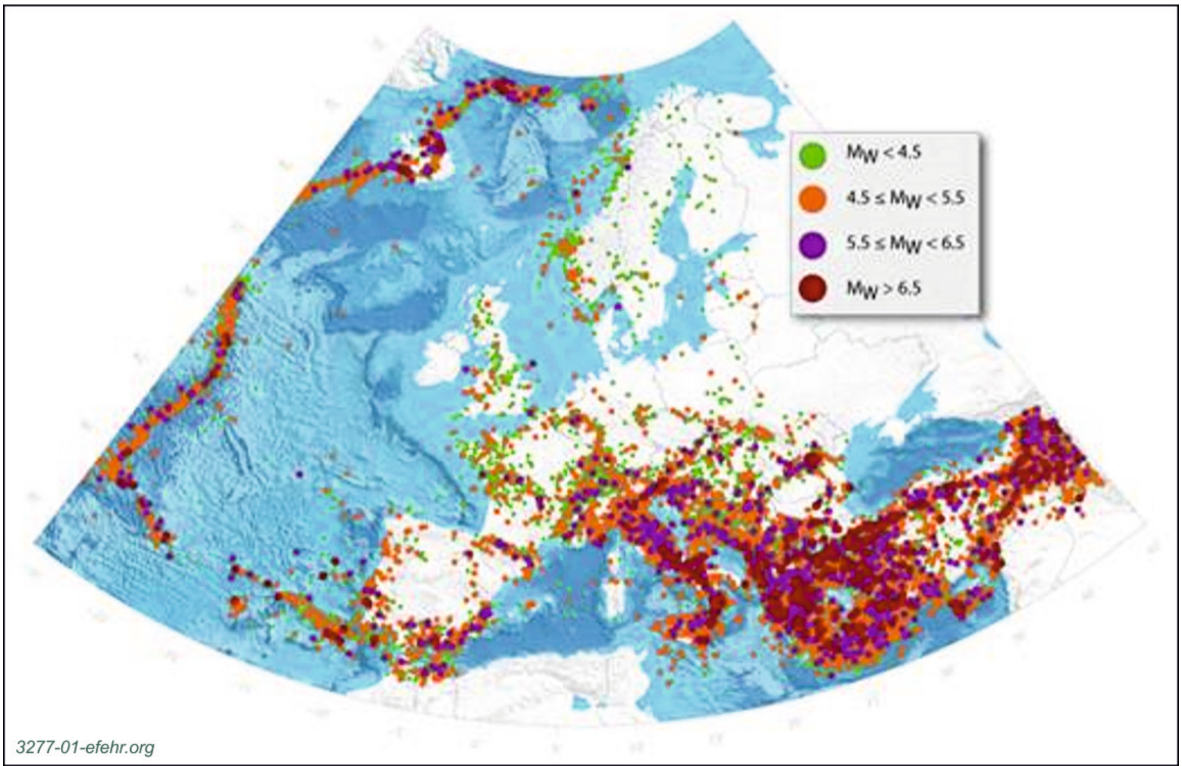
Plate tectonics is of potential relevance, and the implications of earthquakes on a UK GDF will require an appropriate level of consideration at a site-specific stage.

The response of the Earth's lithosphere to convection in the underlying asthenosphere is described by plate tectonic theory [116], wherein strong lithospheric 'plates' establish relative motions with respect to each other, riding on a weaker asthenosphere. Many of the geological and topographic features evident at the Earth's surface stem from the resulting interactions at plate boundaries.

An understanding of the UK's position with respect to plate boundaries is clearly fundamental to identifying those processes that may impact on the post-closure safety case for the GDF. Also, understanding the rates of tectonic processes will provide limits to their potential impact on the GDF site in the time frame considered. For the UK, which is in a relatively tectonically quiescent position at the present time, this will be based on an understanding of past tectonic evolution and the present day stress regime.

Various interactions at active plate boundaries generate distinct geological processes, structures and landforms. These include zones of subduction of dense oceanic lithosphere or collision of continental lithosphere; both these types of plate boundaries are marked by linear belts of deformation (major fault zones, crustal thickening or thinning) and are typically the focus of more frequent, higher magnitude earthquakes and development of volcanoes and igneous intrusions. At present the UK sits in a stable continental setting on the passive continental margin of the Atlantic Ocean and is not close to a margin where active tectonic processes are happening (Figure 14). However, in the future, the Atlantic Ocean will start to contract, subduction will expand along the passive continental margins and the UK will eventually become closer to an active plate margin. The timing of the onset of this process and the rate at which it progresses are clearly the important factors in determining the impact of tectonic process on a UK GDF. Because ocean closures occur over 10's Myr timescales, and only limited or nascent subduction is currently occurring in the Atlantic [117], the 1 Myr period of interest to UK GDF safety is probably a highly conservative estimate of when tectonic change is likely to affect the UK (this issue will be considered further as the GDF site selection process progresses towards site-specific assessments).

Figure 14 Data of all registered earthquakes in Europe and the Mediterranean region, as compiled in a catalogue by the SHARE (Seismic Hazard Harmonisation in Europe) Consortium, covering the period 1000 - 2007 with moment magnitudes $M_W \geq 3.5$[7]. (Graphic: www.efehr.org) [118] (see [119] for further on M_W).



4.1.2 Why is plate tectonics important to the post-closure safety of the GDF?

The effects of plate tectonics present a number of potential hazards for radioactive waste disposal. Fault displacement, caused by mechanical failure in response to plate stresses, has the potential to disrupt the waste emplacement should a fault plane intersect it. Earthquakes (seismicity) are the result of instantaneous fault movements and may give rise to vibratory hazard.

The effects of plate tectonics, in particular earthquakes, igneous intrusions and volcanoes, present a number of potential hazards for the long term safety performance of the GDF.

Fault displacement (rupture) hazard results from physical movement along a fault plane. This is caused by mechanical failure in response to plate stresses and has the potential to

[7] The size of an earthquake is defined by a single, absolute value to describe the magnitude scale. The local magnitude scale (M_L), also popularly known as the Richter scale, is a quantitative logarithmic scale; a simple numerical scale is used to describe the relative sizes of earthquakes. The local magnitude scale was not designed to be applied to data with distances to the hypocentre of the earthquake that were greater than 600 km; this scale also saturates at around local magnitude 7 events, because the high frequency waves recorded locally have wavelengths shorter than the rupture lengths of large earthquakes. Because of the limitations of such a scale, a new, more uniformly applicable extension of them, known as moment magnitude (M_W) scale for representing the size of earthquakes, was introduced in 1977. In particular, for very large earthquakes moment magnitude gives the most reliable estimate of earthquake size, and makes it easy to objectively compare the sizes of different earthquakes.

disrupt the waste emplacement should an active fault plane intersect it. Earthquakes (seismicity) are the result of instantaneous fault movements and may give rise to vibratory hazard. Earthquake hazard, as conventionally assessed, is the vibratory hazard resulting from the passage of surface waves and these have little effect at possible GDF depths. Thus, while vibratory hazard is of concern for the stability of surface installations in an earthquake, it is not likely to affect the safety of the GDF. Rupture hazard could potentially cause disruption to the engineered barriers if they were intersected by the fault plane that moved, but in general the amount of displacement accompanying UK earthquakes is extremely small and takes place at significantly greater depths than the GDF.

Secondary hazards arising from fault movement and earthquakes include disruption of groundwater patterns in response to the alteration of fracture networks, and the generation of tsunami when fault movements rupture the sea-floor.

Hazards associated with a nearby volcanic eruption or igneous intrusion would include melting or heating of the GDF, affecting both the engineered and natural barriers, and secondary disruption of groundwater patterns. The presence of a heat source would drive hydrothermal circulation, heating the groundwater and modifying its hydrochemistry, potentially increasing the rate of corrosion of the engineered barriers and impacting on their containment function. Hydrothermal circulation could also alter the host rock and surrounding rocks, modifying their mechanical and chemical properties. There is however no realistic likelihood of volcanic activity taking place in any part of the UK over the time span of interest for the safety of the GDF.

4.1.3 Tectonic evolution of the UK

The UK is currently located in a stable continental setting characterised by low seismicity.

Although the UK is currently located in a stable continental setting characterised by low seismicity (Figure 14), the geological record preserves evidence of a complex tectonic history. Overprinting of multiple plate tectonic cycles, where some areas of the UK have been formerly located at active plate margins and in continental collision zones, has locally left a legacy of heterogeneous crust that will need consideration in, and may have an impact on, the design of the GDF.

Although Precambrian rocks exposed in the UK provide evidence for older tectonic events, the main structural grain of the UK was imparted by assembly of the continental plates of Laurentia, Baltica and Gondwana during early Palaeozoic times. This assembly involved transfer of fragments of Gondwana (modern West Africa and western South America) onto the Laurentian continental margin during closure of the Iapetus Ocean, which took place between around 515 and 420 Myr. The resulting belt of deformation extends from northern Greenland, through the British Isles and down the eastern seaboard of North America into Mexico and is known as the Caledonian-Appalachian Orogen. Subsequent closure of the Rheic Ocean assembled the main part of Gondwana onto Laurentia between around 400 and 300 Myr. This final collision formed a zone of deformation that extends through southern Great Britain and much of central Europe and is known as the Variscan Orogen [120].

The British Isles themselves formed as an amalgamation of fault-bounded crustal fragments (terranes) that have their roots in the Precambrian building blocks that were originally dispersed along the Gondwanan continental margin. These terranes are predicated on the location of major geophysical lineaments, fault zones and the stratigraphy and architecture of adjacent penecontemporaneous sedimentary basins. In England and Wales these are dominated by a wedge-shaped region underlying the English Midlands which is referred to as the Midlands Microcraton or Midlands Platform. To the west of this there is a strong northeasterly grain to the structures, while to the east there is a northwesterly trend. The Midlands Platform is truncated along its southern margin by westerly-trending structures associated with the Variscan deformation. Extensional faults around the west and south coasts control the distribution and thickness of Mesozoic sedimentary basins.

4.1.4 The current tectonic regime of the UK

A key component of the current stress regime affecting the UK is provided by the present day relative movements of tectonic plates. The seismic hazards related to the GDF are largely controlled by the alignment of existing fault planes within the current stress field and their propensity to reactivate.

Discontinuities in the rock mass (fractures, faults, joints, interfaces, etc.) play a pivotal role in controlling the movement of any groundwater and gas. The transmissivity of discontinuities is strongly dependent upon orientation with respect to the stress tensor; deviatoric stresses (equating to the difference between measured and hydrostatic stresses) can determine whether fracture sets are transmissive at depth.

A key component of the current stress regime affecting the UK is provided by present day relative movements of tectonic plates. Other factors that locally modify the stress field include uplift and subsidence in response to mantle plumes and mantle underplating, glacial isostatic adjustment and denudational isostasy and are considered later in this section [121, 122, 123]. The seismic hazards related to the GDF are largely controlled by the alignment of existing fault planes within the current stress field and their propensity to reactivate. Evidence for the current tectonic stress regime is provided from focal mechanisms derived from instrumental measurements of earthquakes and fault-plane solutions. Other stress tensor estimates based on well-bore breakouts, drilling-induced fractures and in-situ stress measurements are influenced by additional near surface processes. Evidence from earthquake focal mechanisms shows that the modern UK lies within a broadly northwest-southeast compressive stress regime (σ_1) and a southwest-northeast minimum stress (σ_3) [124]. This stress field is attributed to plate forces exerted by the separation of Europe from North America, as well as the roughly northerly movement of Africa relative to Eurasia [125].

Although recent sedimentary basins are not preserved onshore in the UK, post-Miocene strata (younger than c. 10 Myr) preserved in the North Sea do not record a history of basin inversion, indicating that shortening strain associated with the current stress field is relatively low. However, earthquakes are still felt in the UK as the result of distributed strain deeper in the crust (Figure 15).

In situ stress measurements from UK boreholes (Figure 16) indicate that at depths greater than about 500 m, the vertical (overburden) stress is intermediate ($\sigma 2$) between two orthogonal horizontal stresses. Such a stress regime is compatible with strike-slip rather than compressive or extensional faulting.

Earthquake source mechanisms provide both fault geometries and principal stress directions that can be used to constrain the understanding of the driving forces of current deformation. Reference [124] presents a compilation of focal mechanisms for UK earthquakes in the magnitude range M_L 3 to 5.4. The focal mechanisms (Figure 17) were confirmed to be dominantly strike-slip, with a northwest-southeast compression and northeast-southwest tension, or reverse, with northwest-southeast compression. In many cases there is also an oblique component to the slip. Pressure (P) and tension (T) axes represent the axes of maximum shortening and maximum extension on a fault plane respectively. In the UK, P- and T- axes from individual solutions are relatively well constrained in azimuth, though less so in dip, with P-axis orientation for most events clustering between north and north-west, indicating sub-horizontal compression. However, some spatial variation in P- and T-axes' orientation is apparent, with near north-northeast compression and east-west extension in northwest Scotland, changing to northwest-southeast compression in England and Wales.

Seismicity associated with past glaciations that have affected the UK is discussed in Section 4.1.9, together with related information on how glaciation has affected the state of stress.

Figure 15 Instrumental (red) and historical (yellow) seismicity of the British Isles from the British Geological Survey earthquake catalogue (after [126]). Earthquake symbols are scaled by magnitude M_L.

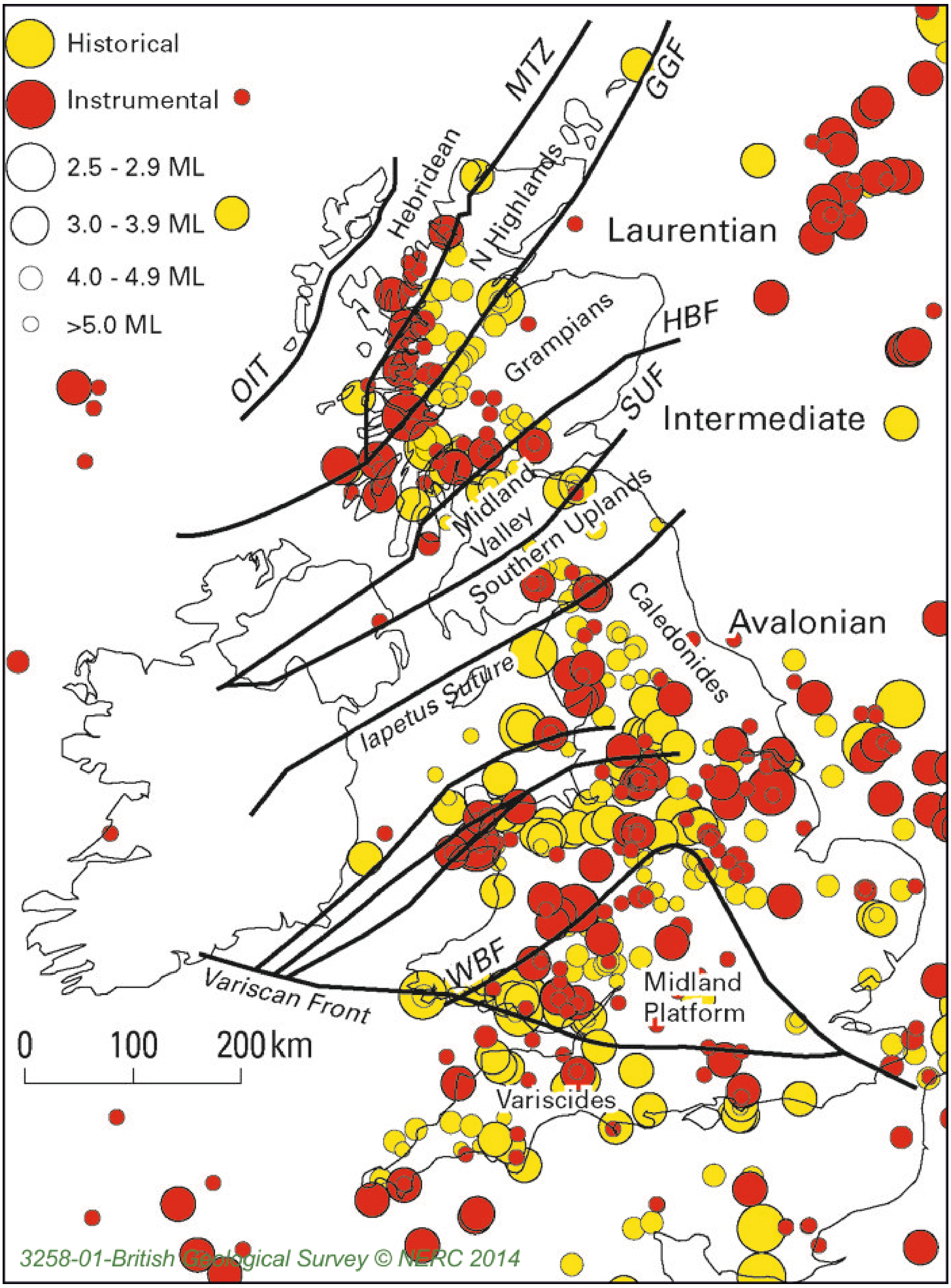


Figure 16 Crustal stress data from selected UK boreholes (adapted from [127]). Note that at depths >600 m, σ2 is vertical, that is, a strike slip regime.

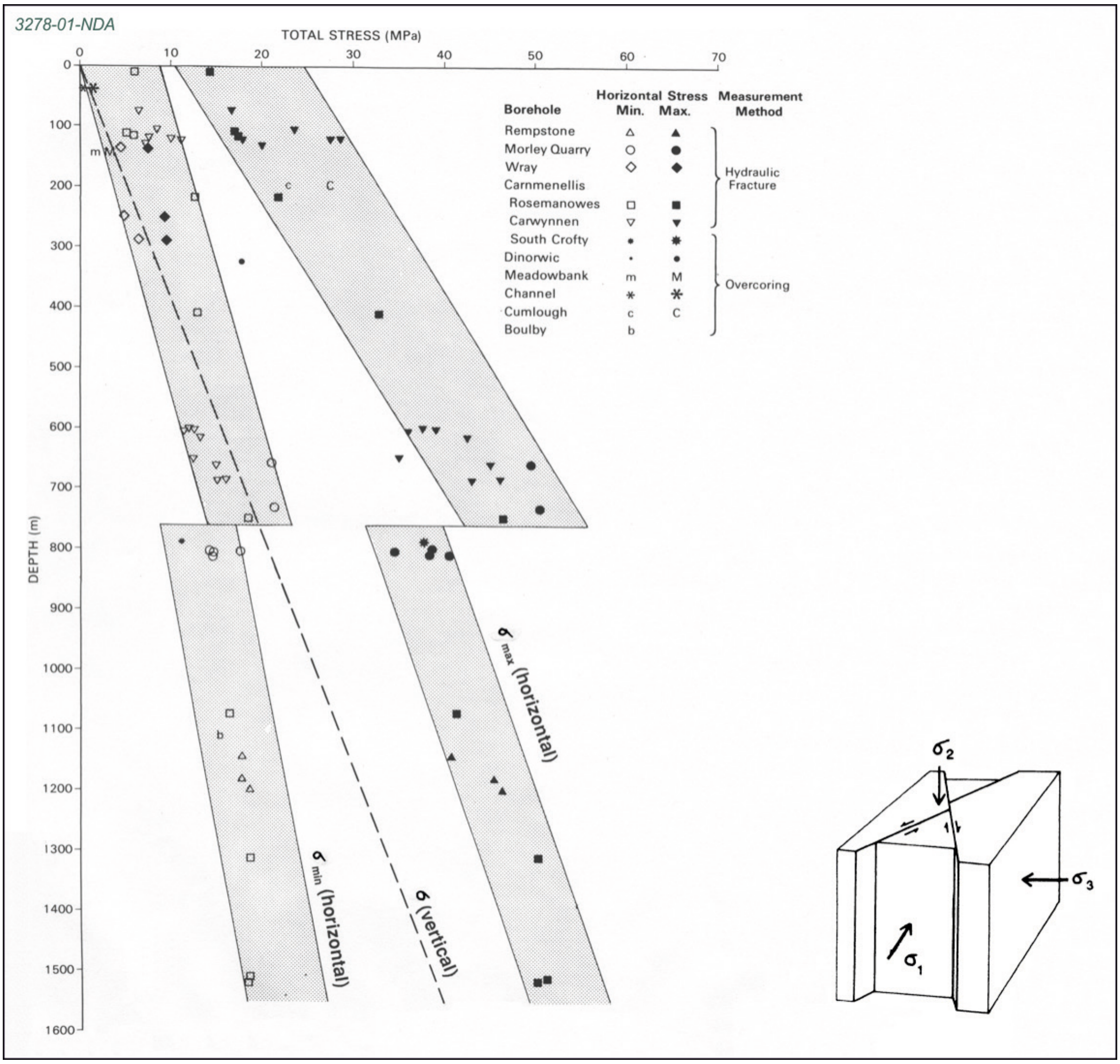
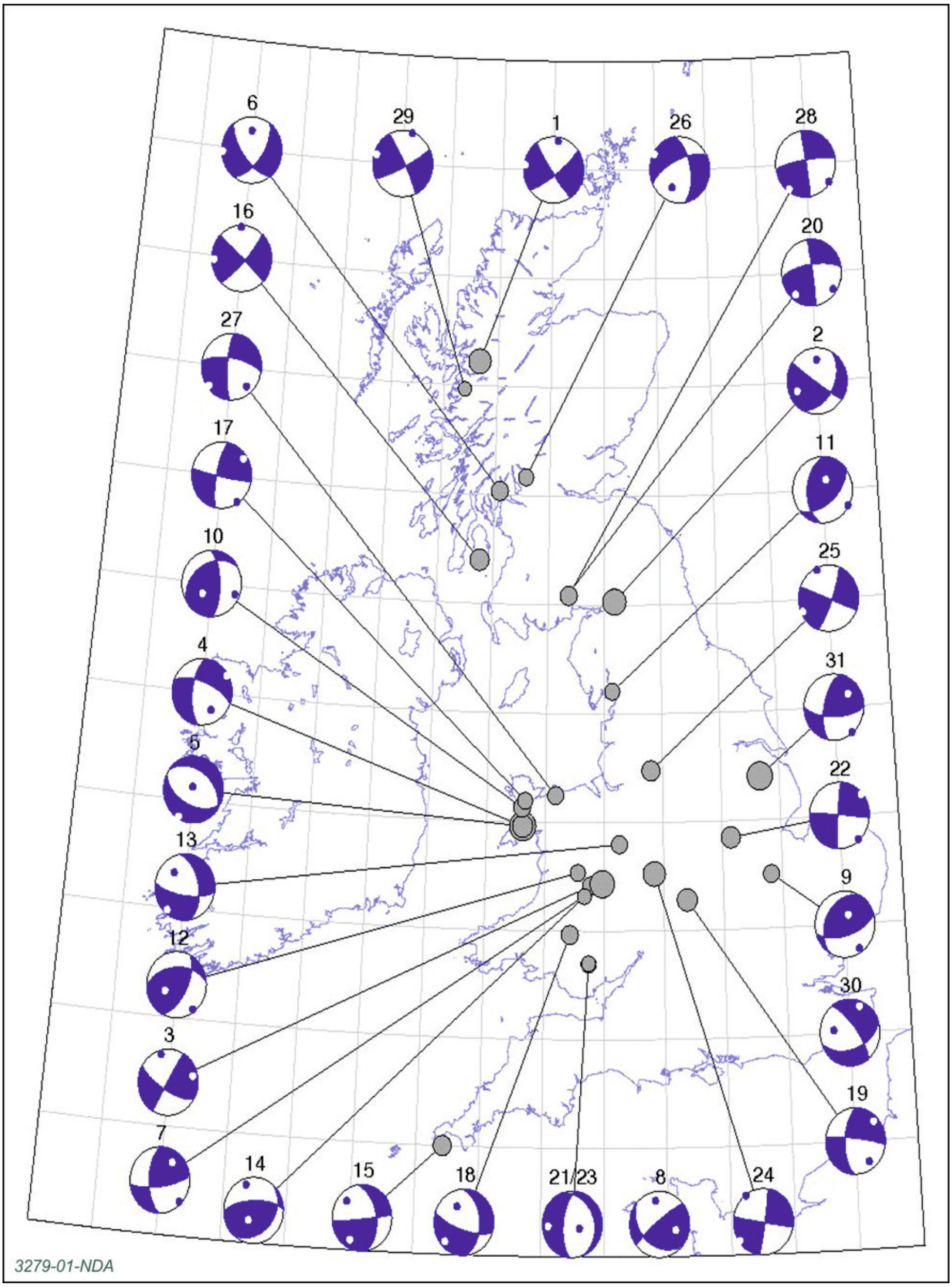


Figure 17 Focal mechanisms for all earthquakes, from [124]. The compressional quadrants are indicated by the blue shaded areas. P- and T- axes are indicated by the smaller blue and white circles respectively.



4.1.5 Seismic hazard in the UK

Vibratory hazard (shaking of the ground) is primarily important very near to, or on the surface of, the Earth. Fault rupture hazard is dependent on rupture depth, which in the UK will usually be much deeper than the depth of the GDF.

There are two types of seismic hazard that might impact on the GDF. One is the vibratory hazard, that is, shaking of the ground, and the other is the fault rupture hazard. Vibratory hazard is primarily important very near to, or on the surface of, the Earth. Fault rupture is very site-specific, and the associated hazard is dependent on rupture depth and extent of affected fault plane. Rupture depth in the UK will usually be very much deeper (for example, by 10s of kms) than the depth of the GDF.

Current good practice in assessing seismic hazard in stable continental regions utilises a probabilistic approach in which the likelihood of exceeding peak ground acceleration over a specified return period is calculated by considering the spatial distribution of earthquakes in a given region, the magnitude and recurrence relationship for those earthquakes and the likely ground motions as a function of distance from the seismic source. The first probabilistic seismic hazard map for the UK was produced by Musson and Winter (see [128]). The UK was also included in the Global Seismic Hazard Assessment Program (GSHAP, [129]) and the Seismotectonics and Seismic Hazard Assessment of the Mediterranean Basin (SESAME) [130] study. Musson and Sargeant [131] published seismic hazard maps for the UK for seismic zoning in relation to Eurocode 8 [132]**.** These studies considered ground acceleration at the surface, not GDF depths. The seismic hazard at the depth of any GDF will be very much lower than the values estimated for surface conditions [133, 134, 135, 136, 137], which are in any case very low.

Estimating the largest earthquake that can be expected in the British Isles in the current tectonic regime is difficult because of the low seismicity rates and the limited history of observation. However, the maximum magnitude is proportional to the amount of fault displacement; it therefore has implications for GDF design. Predictions from a range of studies provide maximum values ranging between 5.5 Mw and 6.5 Mw [121, 131, 138].

4.1.6 Potential impact of fault rupture hazard on a UK GDF

Fault rupture hazard for the GDF developed at between 200 and 1000m depth in the British Isles is very low.

The fault rupture hazard for the GDF developed at between 200 and 1000 m depth in a low seismicity intraplate region such as the British Isles is very low [131]. Published data for larger UK earthquakes suggest that most events with magnitudes of 4.5 M_w or greater tend to nucleate at depths of at least 10 km or greater [131]. Although scattered, the relationship between magnitude and depth for UK earthquakes confirms this. Fault rupture dimensions for the largest recorded earthquakes in the UK are typically of a few kilometres, so that, although a rupture that nucleates at depth may propagate upward, the potential for it to reach the surface is limited. No UK earthquake recorded either historically or instrumentally is known to have produced a surface rupture, although a detailed study of potential surface rupture is likely to be required at any proposed GDF site [126]. As displacement on a rupture plane could damage the engineered barrier system of the GDF, site-specific studies regarding displacement on a rupture plane in a UK context will be considered in the future programme; similar studies undertaken to date by the Swedish waste management organisation (SKB) resulted in the following design requirement with respect to shear movements associated with an earthquake:

> "*The copper corrosion barrier should remain intact after a 5 cm shear movement at 1 m/s for buffer material properties of a 2,050 kg/m^3*

Ca-bentonite, for all locations and angles of the shearing fracture in the deposition hole and for temperatures down to 0°C. The insert should maintain its pressure-bearing properties to isostatic loads…" [139].

4.1.7 Potential impact of vibratory hazard on a UK GDF

Ground motions at, or near the surface, during earthquakes are greater than those at depth, so shaking hazard for the GDF is less severe than for a structure at surface.

A number of studies have examined the differences between ground motion at the surface and at depths of ~100 to 1000 m (such as [126, 134, 135]). These show that ground motions at or near the surface are greater than those at depth as a result of greater amplification of seismic waves in low velocity, near surface, geological materials.

Several studies documenting earthquake damage to underground structures such as tunnels (see, for example, [137]) conclude that they suffer appreciably less damage than surface structures. This evidence suggests that the shaking hazard for a buried GDF is less severe than for a structure at the surface. A conservative estimate might be a reduction in ground motion by a factor of two. However, this is likely to vary with seismic velocity and attenuation specific to a location [137].

4.1.8 Impact of seismically-induced hydrogeological change to a UK GDF

Hydrogeological changes have been widely observed after some large earthquakes. Significant changes to fracture networks can bring about permanent changes in permeability.

Earthquake-related hydrogeological changes, such as the creation of new springs, changes to water-table levels and increased groundwater discharge, have all been widely observed after some large earthquakes [140]. These occur as a response to fault-movement induced pore-pressure gradients enabling water displacement. Water level changes of several metres have been observed, although the effects generally decay rapidly with distance and time from the earthquake and it is improbable they will present a hazard to the GDF [141]. Similarly, dilation and contraction of fractures in response to the stress change accompanying an earthquake have also been linked to movement of deep crustal fluid [142, 143]. In fault zones subjected to repeated rupture, significant permanent changes to the surrounding fracture network can bring about permanent changes in permeability [144].

As well as changes in the deeper fracture network, the deformation associated with earthquakes can also bring about permanent changes in the near surface, manifested as consolidation and compaction of soils. These may be associated with liquefaction of near surface soils and have the potential to alter surface recharge characteristics in the geological environment.

It is important to emphasise that these major changes are only associated with large earthquakes that are not known historically in the UK. For example, increase in discharge from streams is mainly observed at magnitudes of 6.4 Mw and above, although there are a few documented examples at lower magnitudes, suggesting that the hazard is low for the maximum magnitudes expected in the UK [145]. Nevertheless, permanent changes to porosity and permeability resulting from fault rupture and deformation during an earthquake require consideration as potential hazards to the GDF.

4.1.9 Glacial isostatic adjustment (GIA), glacially induced faulting and post-glacial seismicity

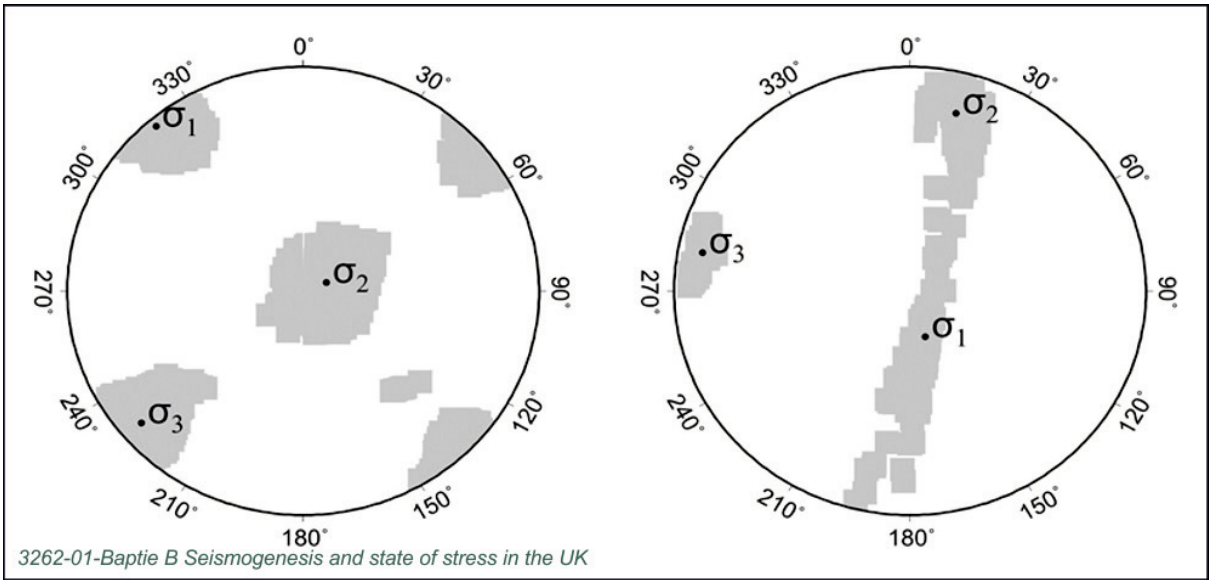
Seismicity recurrence and magnitude following any future glacial period may be significantly higher than at present.

Glacially induced faults (GIF) are taken to include fault movements that are related to the evolution of the ice mass and that may occur during a post-glacial rebound (PGR). GIFs in the northern hemisphere are largely recorded in intraplate settings of low seismicity and have been observed to reactivate existing faults [146]. Most accepted GIFs are located in Fennoscandia and typically have a reverse sense of motion, with seismicity reaching M 7-8 [147, 148]. Reference [149] considers possible examples of GIF in Ireland.

In the UK evidence for seismicity associated with glacial isostatic adjustment (GIA) is provided by a cluster of earthquakes which occurred in the northwest of Scotland, coincident with the region of maximum uplift and interpreted thickest ice accumulation (see also Section 4.3.3). The stress tensor interpreted from this group of earthquakes contrasts with the regional tectonic stress in that the interpreted principal compressive stress (σ1) is vertical and is close in magnitude to the intermediate stress (σ2), with a near east-west extensional component (σ3). This modified stress field has been interpreted to reflect a component of GIA modifying the normal regional stress field [124].

Figure 18 shows best-fitting stress tensors for two different subsets of the data, suggesting that there is a significant difference in the stress state in England and Wales (left) compared to northwest Scotland (right).

Figure 18 Best-fitting stress tensors for two different subsets of the data, suggesting that there is a significant difference in the stress state in in England and Wales (left) and in northwest Scotland (right). The 95% confidence intervals are indicated by the shaded areas. From [124].



A number of studies (for example, [150]) suggest that earthquake activity beneath an ice sheet is likely to be suppressed, followed by much higher levels of activity after the ice has retreated again. Consequently, estimates of seismicity based on current rates may provide an inaccurate estimate of the possible levels of activity that could occur during future glacial cycles. It should be noted that the largest stress changes occur at the former ice margins, making these the most likely source region for enhanced earthquake activity. The implication for the GDF in such a region is that seismicity recurrence and magnitude following any future glacial period may be significantly higher than at present. Given our current maximum magnitude in the UK of 6.1 [126], it is not unreasonable to expect an increase in the maximum possible magnitude to 7 following such an event.

4.1.10 Impact of tsunami hazard on a UK GDF

During the operational phase of the GDF in a coastal location, a tsunami could result in a sudden ingress of potentially large volumes of water into the location of surface facilities. This hazard will be managed by GDF design choices.

Tsunami will have negligible impact on the post-closure safety of the GDF once sealed and protected from water ingress. However, during the operational phase of the GDF in a coastal location, a tsunami could result in sudden ingress of potentially large volumes of water into an inadequately designed facility and therefore the likelihood of such an event needs consideration.

Tsunami are generated either by displacement of the seafloor as a result of earthquake induced surface rupture, or by sediment mass movement events such as a submarine slope failure that may also be triggered by earthquake-induced shaking. In general, only earthquakes with magnitudes in excess of 7.5 Mw are capable of generating tsunami and the main source regions for such events are at plate boundary subduction zones where high magnitude earthquakes can occur at relatively shallow depths [151]. Active plate margins in Japan, Sumatra and South America have all experienced earthquakes of magnitude 8.5 or greater in the last few years that have resulted in tsunami. The nearest subduction zones to Britain lie at the Hellenic Arc, south of Greece and in the Caribbean. Tsunami have occurred in both these regions in historic times, but did not affect the UK. Reference [152] discusses evidence that implies the UK was affected by tsunami 7200 years ago, resulting from the Storegga Slide located offshore mid-Norway.

Recent predictive models of tsunamis in the UK indicate that the most likely scenario for initiating a significantly damaging tsunami would be a large, relatively close earthquake [153] located either in the North Sea or western Celtic Sea, although given the lack of evidence for surface rupture, such rare earthquakes may not be tsunamigenic. Further afield, large earthquakes in the region of the Azores-Gibraltar fault zone have been tsunamigenic, although none have produced any significant impact on the UK coast.

Another potential far field source would be the collapse of the whole of the western flank of the Cumbre Vieja, La Palma, which forms a steep sided volcanic edifice passing into relatively deep water. It has been hypothesised that such a collapse would generate a wave, tens of metres high, which could propagate across the Atlantic and devastate the east coast of America [154]. However, this has been questioned as evidence from surveys of material deposited from previous landslides in the Canary Islands suggests that collapses typically take place as multiple smaller events, over an extended period of time [153]. Consequently if this is the collapse mechanism, the tsunamigenic potential is significantly reduced and the impact restricted to localised areas of scour around the coast.

4.1.11 Impact of volcanic hazard on a UK GDF

Volcanism is not relevant in the UK context over the next one million years.

At present the UK is located within the passive continental margin of the Atlantic. The last volcanic episode ended around 55 million years ago and was related to the opening of the Atlantic Ocean. This episode was responsible for forming the basalt lava flows of Antrim and the volcanic centres of the Hebrides [155]. More intense volcanic activity is expected to occur as the Atlantic contracts and active margins develop, albeit at timescales considerably greater than the 1 Myr timescale.

Given the UK's stable continental setting distal from margins where active tectonic processes are happening (as discussed in Section 4.1.1), it is improbable that volcanism will occur during the next 10 Myr and it is considered implausible that any volcanism will occur in the UK over the next million years.

4.2 Uplift, subsidence and erosion

Subsidence, uplift and erosion have the potential to affect the GDF, as erosion of the cover rock above the GDF could result in a reduction of the geological barrier.

4.2.1 What are uplift, subsidence and erosion?

Tectonic uplift and subsidence are caused by plate tectonic forces of compression, extension and loading. Erosion of uplifted surfaces is driven largely by gravity and the rates are dependent on the mechanical and chemical properties of the rocks, climate, altitude and uplift rate.

All points in the lithosphere are subjected to processes that cause vertical movement and which result in either uplift or subsidence at the surface. These vertical movements of the Earth's surface can vary considerably in scale, distribution and rate. Although they are often controlled by plate tectonics, subsidence and uplift are also linked to other non-exclusive processes affecting the Earth's surface, such as mantle plumes and mantle underplating, post-glacial isostatic adjustment and denudational isostasy.

Tectonic uplift and subsidence
These phenomena are caused by plate tectonic forces of compression, extension and loading. At its most extreme, uplift associated with the collision of continental lithospheric plates gives rise to the development of mountain belts, such as the Himalayas, and broader regions of landscape uplift such as the adjacent Tibetan Plateau. The stretching of continental lithospheric plates, at its most extreme, leads to thinning of the crust, subsidence, rifting and, ultimately, the creation of new ocean basins. Some of the lowest lying areas on the Earth's surface are in these zones of crustal extension, such as the East African rift. Vertical tectonic movements affected the UK most recently in response to the formation of the Alps.

Denudational isostasy
Erosion of uplifted surfaces is driven largely by gravity and the rates are dependent on the mechanical and chemical properties of the rocks, climate, altitude and uplift rate. High uplift rates generally correlate with high erosion rates. Equally, subsidence is generally accompanied, or driven by, loading of sediments onto the sinking surface, supplied by material eroded from the adjacent, relatively uplifted flanks [156]. Both the processes of deposition and erosion can drive crustal flexure and are often driven themselves by other uplift/subsidence mechanisms [157]. In extreme cases, such as in parts of the Himalayas, some authors have argued that coincidence of high rainfall, erosion and uplift rates exerts a control over the location of tectonic deformation (see [158]). A compilation of denudation rates of bedrocks from four climatic categories around the world (Table 2) (m Myr^{-1}), including a Mediterranean-type (warm temperate), temperate (current UK type climate), sub-arctic (boreal, periglacial, forest tundra) and polar (periglacial, permafrost and glacial) climate, shows that the greatest denudation rates occur in orogenic environments such as the European Alps [159] or the San Bernadino Mountains. In these settings bedrock lowering rates of 200 to 700 m Myr^{-1} and 70 to 1200 m Myr^{-1} have been estimated respectively [160]. Typically, bedrock lowering rates (outwith a consideration of glaciation processes) in non-orogenic settings, such as the UK, are much less than 50 m Myr^{-1}. With respect to different rock types, there do not appear to be strong relationships because other factors such as climate (particularly precipitation) would appear to be major determinants.

Table 2 Denudation rates of bedrocks from climates around the world.

Location	Climate	Setting/geology	RWM rock Description	Authors	Method	Rate m Myr^{-1}
Dry Valleys, Antarctica	Polar	Crystalline	Higher Strength	[161]	^{21}Ne	0.26-1.02
Antarctica	Polar	Sandstone (hyper-arid)	Lower Strength	[162]	^{10}Be and ^{26}Al	0.1-1.0
S. Norway	Sub-arctic	Elev. Plain gneiss schist	Higher Strength	[163]	Quartz veins, weathering rinds	0.5-2.2
Eyre Peninsula, Australia	Mediterranean	Granite (semi-arid)	Higher Strength	[164]	^{10}Be and ^{26}Al	0.5-1.0
Pajarito Plateau (NM)	Temperate	Tuff (temperate)	Higher Strength	[165]	^{10}Be and ^{26}Al	1-10
N. Sweden	Sub-arctic	Plain Crystalline	Higher Strength	[166]	^{10}Be and ^{26}Al	1.6
Canada	Polar	Plain crystalline	Higher Strength	[167]	Palaeo-surface reconstruction	2-8
Masanutten Ttn, USA	Temperate	Sandstone, Shale	Lower strength	[168]	Mass Balance	2-10
S. Piedmont, USA	Temperate	Piedmont, granite	Higher Strength	[169]	Mass Balance	4
Baltimore Piedmont, USA	Temperate	Piedmont granite	Higher Strength	[170]	Mass Balance	4-8
Brubaker Mts, USA	Sub-arctic	Low relief Schist, gneiss	Higher Strength	[171]	Mass Balance	4.5-6.5
Rheinsh Massif, Germany	Temperate	Sedimentary	Lower strength	[172]	^{10}Be	4.7-6.5
Iceland	Sub-arctic	Basalt	Higher Strength	[173]	Sediment record	5
Namib desert, S. Africa	Mediterranean	Granite Inselbergs	Higher Strength	[174]	^{10}Be and ^{26}Al	5-16
Haleakala and Mauna Loa (HW)	Temperate	Basalt (various 0-3km elevation)	Higher Strength	[175]	He	7-11
Mt Evans (CO)	Sub-Arctic	Granite erosion of bare surface	Higher Strength	[176]	^{10}Be and ^{26}Al	8
Georgia Piedmont, USA	Temperate	Granite (temperate)	Higher Strength	[177]	^{10}Be and ^{26}Al	8[8]
S. Piedmont, USA	Temperate	Piedmont granite	Higher Strength	[178]	^{10}Be and Residence time	20
Luquillo Experimental	Temperate	Quartz diorite	Higher Strength	[179]	^{10}Be	25
Pacific NW, USA	Temperate	Orogenic	Higher Strength	[180]	Mass Balance	33
S. Blue Ridge	Temperate	Schist, gneiss	Higher Strength	[181]	Mass Balance	37
Smokey Mts, USA	Temperate	Schist, gneiss	Higher Strength	[182]	Mass Balance	38
Boso Peninsula Japan*	Humid-temperate	Sst/mudst. High rates of glacio / eustatic change	Lower Strength	[183]	^{10}Be, ^{26}Al	90-720
European Alps*	Sub-arctic	Orogenic	Higher Strength	[159]	Apatite Fission Track (AFT)	200-700
India*	Mediterranean	Escarpment	Higher strength	[184]	Functional Relationship model	205-275
San Bernadino Mts, California,	Temperate	Orogenic, qtz-monzonite and granodiorite, sst, granite	Mixture	[160]	^{10}Be, Apatite (U-Th/He) thermochronometry	70-1200

8 Note that these are areas of active mountain building which consequently have much higher denudation rates than occur in mid-crustal locations such as the UK.

Glacial isostasy
Relatively short-term glacio-hydro-isostatic induced uplift and subsidence are typical lithospheric responses to loading during glacial advance and retreat, the effects of which are increasingly recognised as providing significant uplift (of the order of several hundred metres to kilometre scales) in some regions of the North Atlantic margin and adjacent continental hinterland [185].

Erosion associated with glaciation (including glacial scouring) needs consideration; glacial over-deepening can create valleys deep enough to potentially affect the GDF.

Mantle plumes and underplating
Impingement of low density thermal anomalies associated with partial melting of the asthenosphere can cause up-doming in the overlying lithosphere. This is typically associated with mantle plumes or underplating of mafic magmas [186].

4.2.2 Why are uplift, subsidence and erosion important to the post-closure safety of the GDF?

Uplift and accompanying erosion could affect both the isolation and containment functions of the GDF.

Subsidence, and accompanying burial by deposition of sediment, would result in increased isolation of the waste in the GDF, enhancing its capacity to isolate the waste from the biosphere for the long term. Conversely, uplift and accompanying erosion could affect both the isolation and containment functions of the GDF. Not only have the processes of uplift and erosion the potential to decrease the thickness of the natural geological barrier above the engineered barriers, they could result in the eventual exposure of the waste. Reducing the thickness of the overlying geological environment could also substantially alter the hydrological regime; the direction of flow in any over- and underlying aquifers could be altered and new pathways formed that could potentially transport radionuclides rapidly to the surface. Internationally, geological disposal programmes consider the impacts of uplift and erosion to be more significant than subsidence and burial [156].

4.2.3 Recent uplift and subsidence in the UK

During Neogene times, the UK experienced considerable uplift attributable to a number of causative mechanisms. More recently, uplift and subsidence of a lower extent affect the UK, relating primarily to glacio-isostasy. Annualised, average uplift and subsidence rates are at the sub-millimetre scale.

Over the last 23 Myr, during the Neogene and Quaternary periods, the UK has seen considerable uplift, in particular an estimated 1 km of exhumation during Neogene times [187, 188, 189] and consequent non-preservation of onshore Miocene age deposits in the British Isles [190]. This has been attributed to a variety of non-exclusive processes, including uplift above mantle plumes or underplating by mafic magmas associated with Atlantic extension [122, 191, 192, 193, 194], Late Alpine collisional effects and ‘ridge-push’ from the Atlantic, which was spreading at this time, as well as deglaciation [195].

There is an emerging consensus amongst the scientific community that ongoing uplift in the north of the UK and complementary subsidence in the south, as well as uplift across Europe and the north-east Atlantic margins, together with contemporary seismicity in the UK, are driven largely by glacio-isostasy [126, 195, 196, 197, 198, 199]. Other non-exclusive processes, including lithospheric stretching beneath the North Sea [200] and continuation of an Atlantic thermal anomaly [122, 123] have also been proposed.

In support of glacio-isostasy as the principal driver for ongoing vertical movements, recent earthquake studies have shown that contemporary seismicity in the Scottish Highlands is concentrated in the area of expected maximum glacio-isostatic uplift, coincident with Late Quaternary shoreline dislocations, faults and palaeoseismic phenomena [126, 198].

4.2.4 Future uplift and subsidence impacts on a UK GDF

Cycles of glacial advance and retreat are likely to affect the UK in the future.

1. **Tectonic change:** It is likely that further deformation will take place in the UK, but only on a very long timescale. The timing is expected to be greater than 1 Myr and is therefore not likely to impact on a UK GDF
2. **Ongoing post-glacial isostatic adjustment and future glaciation:** Future climate models predict that cycles of glacial advance and retreat are likely to affect the UK in the future. These are described further in Section 4.3.3 and are considered to have a greater probability of impacting a UK GDF in the future
3. **Future denudational isostasy:** Denudational isostasy is active in the UK at present [201] and is predicted to act in tandem with other drivers of uplift in the future. The rate of denudational isostasy will be influenced by erosion rate, in turn linked to climate. Future climate models for the next 200 kyr predict alternating glacial and interglacial periods (see Section 4.3.2). For parts of the UK, the glacial periods will include glaciations (active ice cover) while unglaciated areas will experience permafrost conditions. During the intervening interglacial periods, the UK will experience cool to warm temperate climates.

4.3 Climate evolution, in particular the impact of glaciation, permafrost and sea-level change

External, climate driven processes and related phenomena such as permafrost development and periods of glaciation, could potentially impact on a UK GDF.

Most long term climate models forecast that the northern hemisphere will experience further cycling between glacial and interglacial periods over the next one million years [202], even with consideration of anthropogenic climate change. Therefore, a UK GDF is likely to experience glaciation and/or permafrost conditions several times over its safety-critical lifetime. Predictions of the duration, thickness and extent of future ice cover are essential to understanding and assessing the impact of these processes on the post-closure safety of a UK GDF. These predictions are largely informed by evidence from past glaciations, outlined below, which in turn are used to validate climate evolution models.

This section describes the range of models developed to predict future climate evolution. This information underpins understanding of the impact of glaciation on post-closure safety, including development of permafrost and frozen ground, glacial isostasy and associated seismic and erosional hazards, eustatic changes in sea level and the impact of these processes on groundwater regimes.

4.3.1 Past evidence to inform understanding of future climate evolution

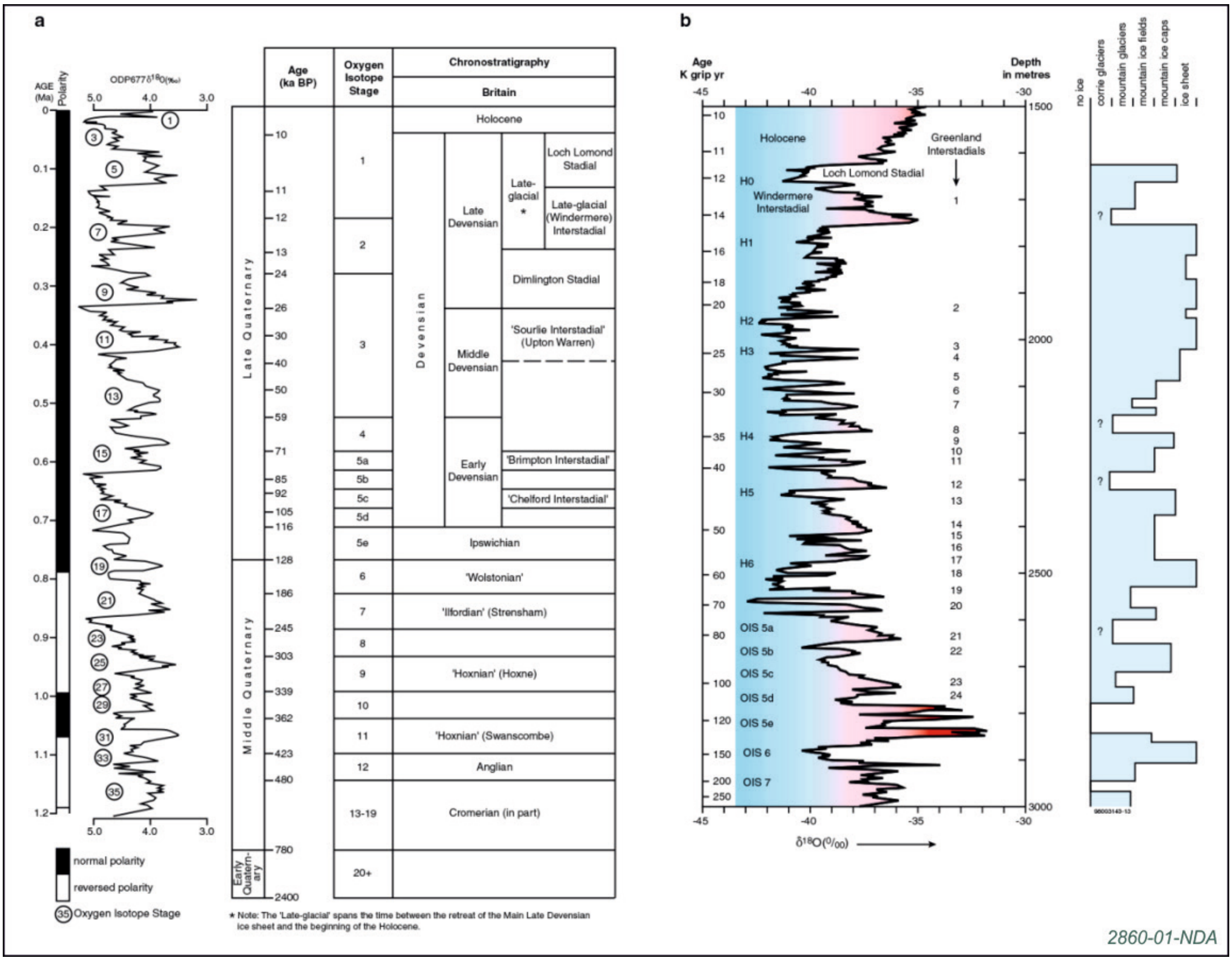
Reconstruction of past British ice-sheets will aid predicting the growth and decay of future ice sheets that may arise during glaciation events. There is evidence, both onshore and offshore, for numerous glaciations in the British Isles. Future glaciations remain the subject of considerable debate. Most models show that the previous ice cover extended over most mountainous areas at its maximum extent and reached thicknesses of over 2 km.

The first evidence for glacial events in the geological record occurs as far back as 2700 Myr and since then the Earth has experienced many glacial episodes [203]. In the more recent geological record, global climate has progressively deteriorated from the greenhouse climates of the early Cenozoic Era (c.55 Myr) through to the current Quaternary Period that spans the last 2.6 Myr [204]. The Quaternary is popularly referred to as ‘The Ice Age’, however the geological record from this time period reveals multiple oscillations between global ‘cold stages’ and global ‘temperate stages’ [205, 206]. Mid-latitude regions, including the UK, have proven particularly sensitive to these global-scale climatic changes, with marked variations in prevailing climate over comparatively short periods of geological time (tens of thousands of years) [207, 208].

The evidence for fluctuation between cold and temperate stages during the past 2.6 Myr is mainly provided by analyses of the deep ocean and some lake drill-cores that preserve a largely intact depositional record over this time interval. Oxygen-isotope analysis of calcareous foraminifera, coccoliths and siliceous diatoms preserved within the sedimentary record has shown a marked variation that reflects preferential partitioning of ^{18}O into seawater rather than glacial ice. This has provided sequential evidence for both short term glacial and interglacial episodes (Figure 19), as well as the longer period cycles at 41 kyr and 100 kyr respectively that were originally identified in the 19th Century by Milankovitch and others as reflecting variations in the Earth’s orbit controlling the amount of solar energy (insolation) that reaches the surface [209, 210]. An independent verification of this variation has been obtained from direct measurement of oxygen-isotope ratios in ice cores from the Antarctic and Greenland (GRIP[9] Summit ice core, Figure 19) in ice sheets which have also persisted through the Quaternary Period.

[9] Greenland Ice Core Project

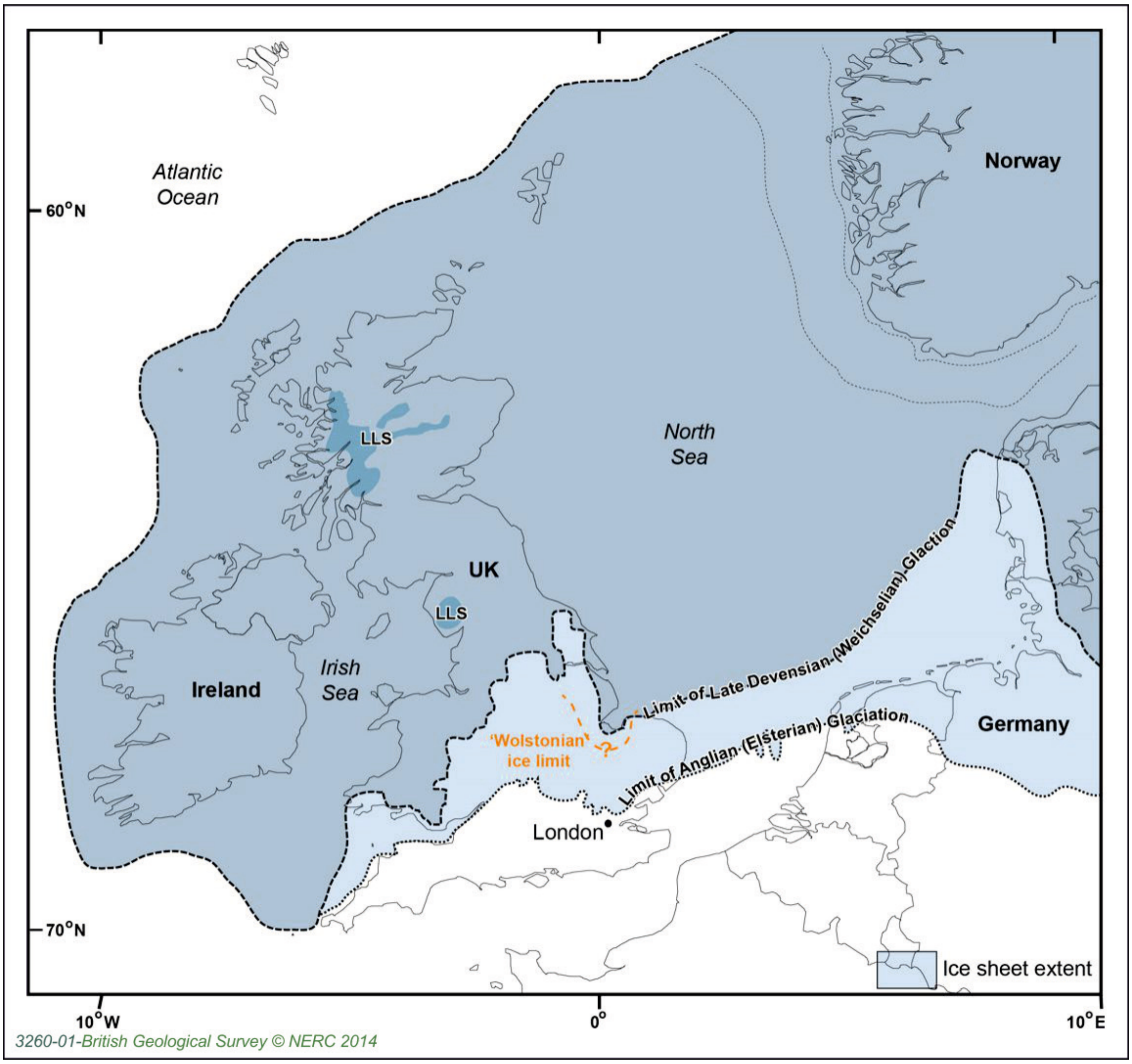
Figure 19 British Quaternary chronostratigraphy and a representative oxygen isotope and geomagnetic polarity record (ODP 677) (modified after [211]); b. Greenland (GRIP Summit ice core) oxygen isotope record. The GRIP timescale was determined by counting annual ice layers back to 14.5 kyr BP; and beyond this time by estimation based on ice-flow modelling.



In the UK, onshore evidence for Quaternary climate is less complete as the geological record is dominated by glacial deposits and erosional landforms formed during the latest glaciation, which has largely destroyed evidence of previous glaciations. However, correlation with the more complete marine record has been achieved by analysis of scattered cave and lacustrine deposits. This has highlighted the predominance of four glaciations in the UK onshore Quaternary record referred to as the Younger Dryas (or Loch Lomond Stadial, 12.5-11.7 kyr BP), Late Devensian (30-18 kyr BP), the Wolstonian (186-128 kyr BP) and preceding Anglian (ca. 480-430 kyr BP, Figure 20). The precise number and timing of cold stages in the UK remains speculative, but it is currently believed that Britain has experienced over 30 episodes of glaciation of varying scale during the Quaternary [212, 213, 214, 215].

Relatively small or modest changes in regional (or global) temperature have previously led to the inception of highland glaciers [216, 217].

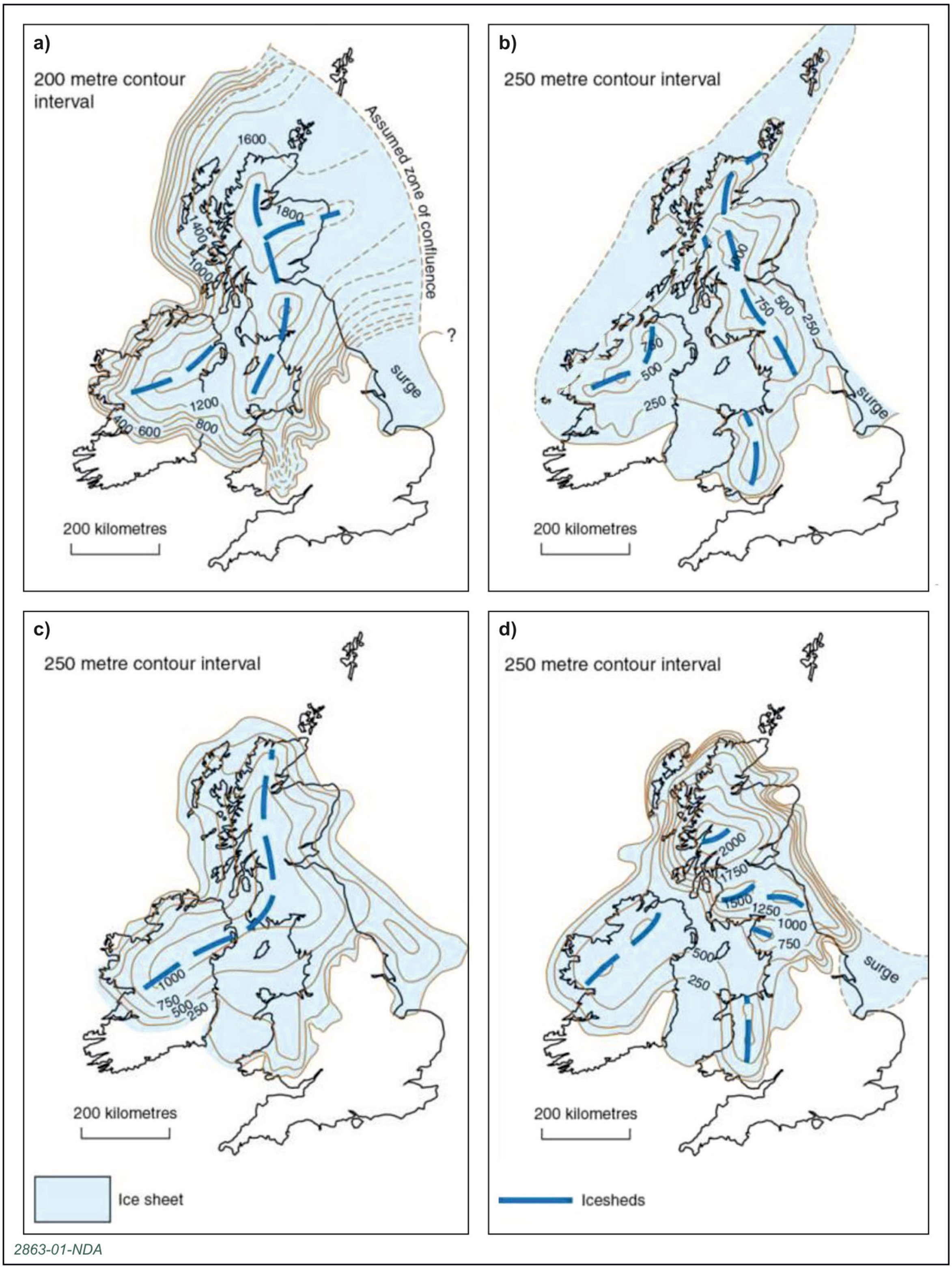
Figure 20 A reconstruction illustrating the maximum extent of ice cover during the Anglian, Late Devensian and Younger Dryas glaciations of the British Isles and limit of Wolstonian glaciation in eastern England and the North Sea. (Modified from [14], principally with data from reconstructions by [218, 219]. British Geological Survey © NERC 2014).



Recently, information on the distribution of glacial landforms and deposits has informed models of growth and decay of the British-Irish Ice Sheet (BIIS). There have been a number of different approaches to this, but largely they seek to reconstruct ranges of ice thickness and extent, variations in ice sheet morphology, basal shear stresses and dynamic thermomechanical conditions [220, 221, 222].

Most reconstructions of the form of the BIIS at the Last Glacial Maximum (LGM) conclude that the ice blanketed even the most mountainous areas of the UK and, at its maximum extent, locally may have reached thicknesses >2 km in northwest Scotland (Figure 21) [223, 224, 225]. No comparable reconstructions are available for earlier glacial events, but the margin of the Anglian ice is interpreted to have extended further south than the main Late Devensian glaciation limit in southern Britain, suggesting that a greater thickness of ice was present over a wider area, and for a longer time [219, 223] (Figure 20).

Figure 21 Models of the BIIS at its maximum extent and ice thickness (a) [226]; (b) [227]; (c) [228]; (d) [229]. Modified after [211].



4.3.2 Models of future climate evolution

A variety of models have been developed to predict future climate. Modelling suggests climates as warm as, or warmer than, the present day are likely to persist in the UK for 170 thousand years, after which a cooling trend is projected to occur.

There is general consensus that since the 'Mid-Pleistocene Revolution' (MPR) c. 0.9-1 Myr BP, the eccentricity of the Earth's orbit has been the dominant 'forcing' mechanism of global climate and glaciations, leading to a cyclicity between glacial and interglacial conditions with periods of ~40 and ~100 kyrs [230, 231, 232, 233]. However, high concentrations of atmospheric CO_2 will raise global temperatures and delay the onset of glaciations [234]. Because the variations in the Earth's orbit that control the amount of solar energy that reaches the surface can be predicted by Milankovitch Theory, future global insolation can be fairly precisely calculated [235] and is used as a basis to model how the climate system responds to orbital forcing in the future.

Over the past few decades, a variety of models have been developed to predict future climate. Reference [236] provides a summary of the role, types and outputs of climate models. Long term forecasts of between 100 kyr and 1 Myr After Present (AP) are typically orbital forcing models (OFMs) based on the assumption that climate change in this time period can be based on the future projection of past trends of Milankovitch cyclicity. Because recent past climate has been dominated by cold versus temperate stage variation these models typically project the timing and duration of future inferred glacial, interstadial and interglacial climate, ignoring anthropogenic and other possible sources of variation [237]. The Imbrie & Imbrie model [237] predicts glacial conditions at 23 kyr, 63 kyr and 100 kyr AP, with the ice sheet at 23 kyr AP extending to the Helsinki-Stockholm region and at 63 kyr AP extending to northern Germany.

Other types of climate models, including Earth Models of Intermediate Complexity (EMICs) and coupled climate-ice sheet models, have been developed to simulate the contribution of various components of the climate system in the transition between glacial and interglacial conditions. Of these the LLN 2D NH model has produced climate simulations for the next 130 kyr, with representations of present-day northern hemisphere ice sheets and different scenarios for future CO_2 concentrations [238]. Without anthropogenic forcing, the next interglacial maximum is expected to be most intense at around 100 kyr AP, after which continental ice will rapidly melt, leading to an interglacial minimum. However, taking account of anthropogenic forcing, the current interglacial conditions will be extended, delaying the onset of a glacial period by approximately ~50-70 kyr. The first major northern hemisphere glaciation is therefore projected under these models to occur between about 170 and 180 kyr AP.

Two other principal EMICs, MoBidiC and CLIMBER-GREMLINS, link ice sheet and climate models together, and have been used as part of the BIOCLIM project. This project modelled sequential BIOsphere systems under CLIMate change for radioactive waste disposal, as part of the EURATOM 5th European Framework programme with the aim of providing a scientific basis and practical methodology for assessing the possible long term environmental impacts on GDF safety. BIOCLIM modelled a range of scenarios that also took into account the impacts of anthropogenic CO_2 and applied them to the LLN2-D NH model [239], and subsequently to the MoBidiC, GREMLINS and CLIMBER-GREMLINS models [240], to compare the effects of climate changes in each and evaluate their ability to simulate past climates. Several global simulations covering the next 200 kyr were performed using CLIMBER-GREMLINS and MoBidiC simulations and were downscaled to provide regional climate estimates for different areas. Three scenarios were presented for future variations in concentration of atmospheric CO_2:

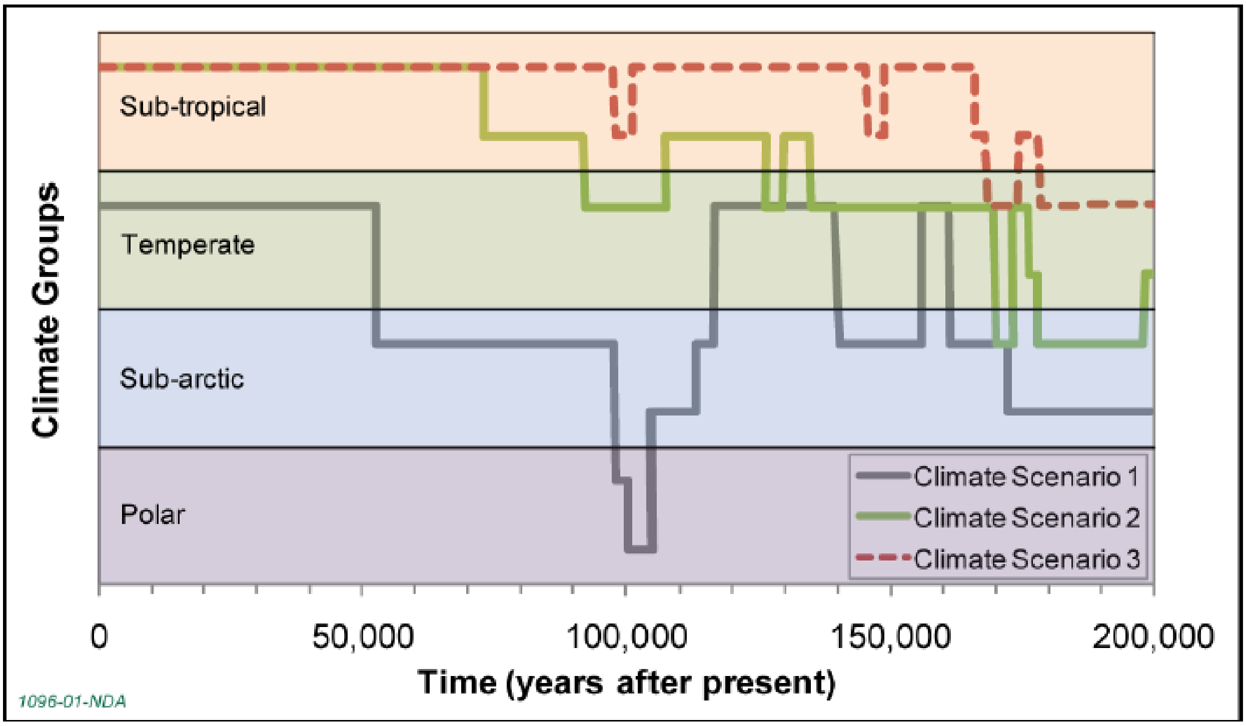
- Climate Scenario 1 (no anthropogenic CO_2 contribution)
- Climate Scenario 2 (low anthropogenic CO_2 contribution)
- Climate Scenario 3 (high anthropogenic CO_2 contribution).

These scenarios were downscaled to specific regions such as central England (Figure 22) and the output is summarised below [241].

Climate Scenario 1 (no anthropogenic CO_2 contribution)
This model scenario predicts that under natural conditions with no additional CO_2 forcing the northern hemisphere continental ice volume will peak at 108 kyr AP, 152.5 kyr AP and 179 kyr AP; these maxima are however characterised by a maximum volume of continental ice that is less than the volume simulated at the LGM. The Eurasian ice sheet will extend south of 60°N only twice over the next 200 kyr, from 105.5 kyr AP to 109 kyr AP and from 175 kyr AP to 180 kyr AP. Both continental ice volume and temperatures tend to show that the climate of the next 200 kyr is globally warmer than the climate of the last glacial-interglacial cycle.

A low volume ice sheet in the UK would be limited to the north-western upland areas, similar to its extent in the Loch Lomond Stadial. In lowland UK, polar tundra conditions would be expected to prevail for a considerable time (c. 50 kyr) prior to the onset of glaciations, along with development of discontinuous (patchy) permafrost in central England.

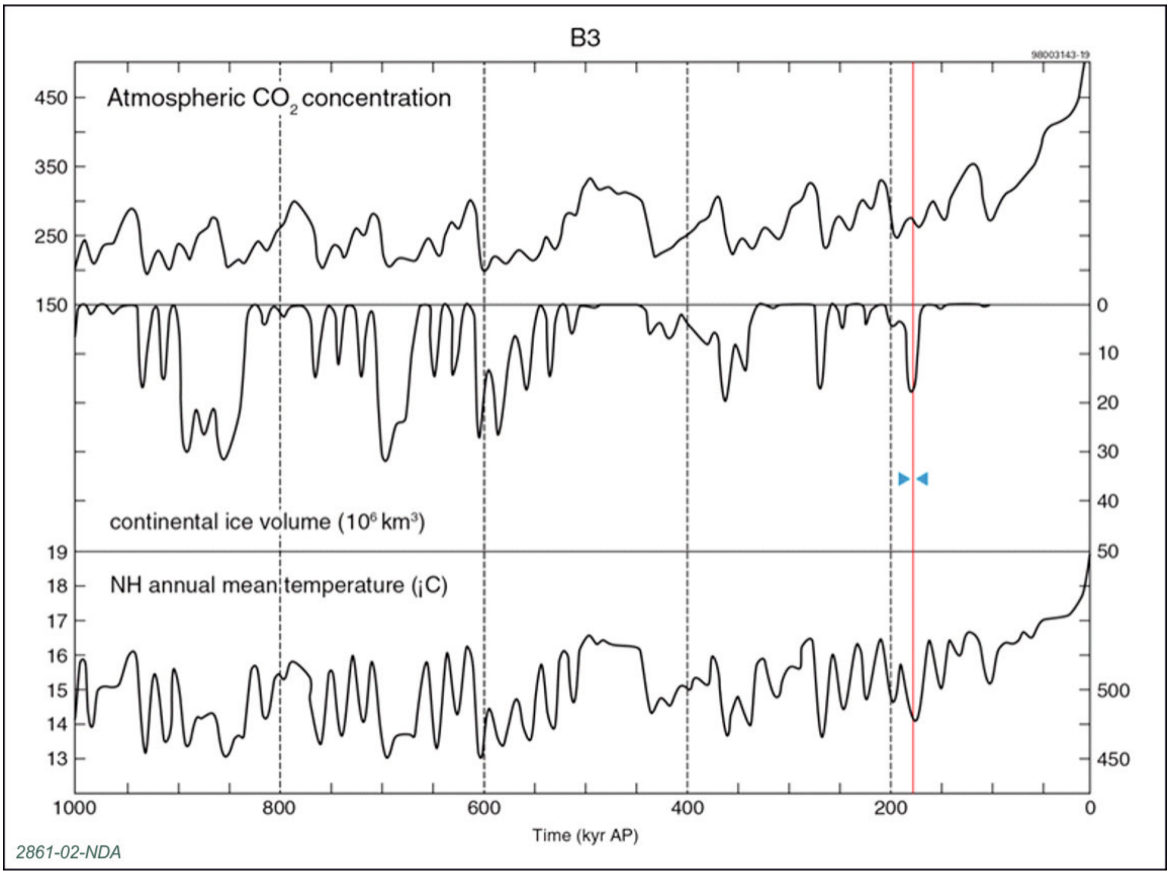
Figure 22 Projected future climate states for central England under the different scenarios. Figure based on BIOCLIM output [242]. Climate scenario 1: No anthropogenic CO_2 contribution. Climate Scenario 2: Low anthropogenic CO_2 contribution. Climate scenario 3: High anthropogenic CO_2 contribution.



Climate Scenarios 2 and 3 (low and high anthropogenic CO_2 contribution)
These model scenarios accommodate the warming effect of anthropogenic CO_2 with an overall rise of about 2 to 3ºC in global mean annual temperature. They predict temperate

conditions similar to those of the present-day until 90 kyr AP and 170 kyr AP respectively, with the high anthropogenic CO_2 contribution scenario predicting temperate conditions throughout the first 200 kyr. For both scenarios, the northern hemisphere will remain free of continental ice for most of the next 200 kyr. The Greenland ice sheet will melt totally over the first few thousand years; at 108 kyr AP and 151 kyr AP some ice will accumulate over Greenland. From 167 kyr AP the significant northern hemisphere continental ice sheets start to accumulate and are modelled to recover to present day levels by about 170 kyr AP. Beyond 200 kyr AP the modelled effects of anthropogenic CO_2 were predicted to decline to negligible levels and from 200 kyr AP to 1 Myr AP 'normal' glacial-interglacial cycling would return at 100 kyr periodicities and persist throughout that time interval (Figure 23).

Figure 23 Northern Hemisphere future model to 1 Myr AP with Intermediate CO_2 forcing. The red line shows the first major glaciation at c. 170-180 kyr AP (modified after [239]).



Further modelling based on these scenarios considered the impact on landscape evolution, in particular ice-sheet development, permafrost and geomorphological evolution [243, 244]. What is evident however, is that many of the climate narratives developed for central England are not directly applicable, without calibration, to much of upland Britain, particularly in the northern and western parts of the country. Here, particularly in mountainous areas, the present day interglacial climate is more severe than in the lowlands, and comparable to some periglacial episodes that affected the lowlands during the Lateglacial Interstadial (13 and 14 ka BP). This is indicated by the active development of periglacial features, such as patterned ground and solifluction lobes[10] in Snowdonia and

[10] A solifluction lobe is a type of slope failure where sediments form a tongue-shaped feature due to differential downhill flow rates.

the Scottish Highlands today (for example, see [245], although [246] proposes an alternative mechanism for the formation of some features).

Reference [247] discussed the limitations of the BIOCLIM modelling. In particular, BIOCLIM work relied on the modelling of EMICs (MoBiDIC and CLIMBER/GREMLINS) that were then at an early stage of development. Since then, the techniques of downscaling from EMICs have improved considerably and new EMIC simulations may be warranted when a site or sites have been selected for consideration to host the GDF, so that downscaling can address the specific geographical contexts of those sites. However, no similar very long term climate studies have since been undertaken. Hence it remains appropriate to rely on the BIOCLIM work, which forecasts that climates as warm as, or warmer, than the present day are likely to persist in the UK for 170 kyr AP, after which a cooling trend is projected to occur [247]. The BIOCLIM modelling indicates that the distinction between the high and low anthropogenic CO_2 contribution cases is lost between about 250 and 400 kyr AP and that it is likely that there will not be a glaciation of the British Isles comparable in extent to the LGM until several hundred thousand years in the future.

4.3.3 Impact of climate change on the post-closure safety of the GDF

Changes in climate can induce a number of changes to the environment pertinent to the long term safety of the GDF:

- Glacial Isostatic Adjustment (GIA) can have a significant effect on uplift well beyond the extent of the former ice sheet
- Permafrost will have an effect on the groundwater regime
- Glacial and sub-glacial erosion result from a cyclical glacial-interglacial climate; during periods of climate change alteration of the landscape can be fast and unpredictable
- In particular, glacial scouring and glacier over-deepening could lead to localised erosion of over 200 m, which could affect the GDF located at the lower end of the expected depth range
- A change in sea-level after closure of the GDF may change the facility's position relative to the coast, or even put it below the seabed.

(a) Glacial Isostatic Adjustment (GIA)

What is GIA and what are its effects?

The concept of glacio-isostasy, the idea that major glacial advances and retreats are accompanied by significant lithospheric deformation, was proposed more than a century ago [248, 249, 250]. It is now understood that the mass applied and removed during the growth and contraction of large ice bodies has a loading effect on the lithosphere leading to flexure and viscous flow in the underlying asthenosphere. This drives changes in land elevation and modifies lithospheric stresses that are more normally dominated by plate tectonic processes. This process has been extensively studied in previously glaciated northern hemisphere regions such as Canada, the United States, Fennoscandia and Siberia, and there is a growing consensus that GIA has been the major driver of high latitude uplift since the LGM [185]. The following sections provide a brief account of the basic concepts underlying glacial isostasy and the evidence for, and nature of, its impact in the UK.

Lithospheric response to ice loading

Outside regions of glaciation, lithospheric stress is generally a response to horizontal plate motions, but with the onset of glaciation the principal compressive stress ($\sigma1$) is typically vertically reoriented under the influence of the overlying mass of ice [117]. In response to this loading, lithospheric flexure results in a 'bowl' of depression below the ice sheet centre, accommodated as the deeper viscous asthenosphere flows radially outward from below the maximum ice load. Horizontal lithospheric motions induced by the ongoing GIA spread out from the centre of the ice sheet and are greatest at the ice sheet margins [251]. Beyond the ice margin, lithospheric flexure is accommodated by radial vertical extension within a forebulge region [196, 252, 253, 254] which may extend for several hundreds of kilometres beyond the ice margin [255].

Post-glacial rebound (PGR)

During the LGM (about 20,000 years ago) much of Asia, North America, Greenland, Antarctica, northern Europe and the central parts of the UK are interpreted to have been covered by ice sheets up to 3 km thick [227], with radii approaching 1000 km in Fennoscandia and 2000 km in Laurentia. Ice sheets in Iceland, the British Isles and the mountain chains of Europe are thought to have been smaller and thinner [254] and may have reached thicknesses >2 km in northwest Scotland (see Figure 21).

As this ice mass contracted, the change in distribution and degree of loading is concluded to have been accompanied by gradual re-adjustment, including uplift of the depressed lithosphere and subsidence of forebulges, with associated denudation and landscape evolution [223]. Readjustment is largely driven by the contrast in buoyancy between the low density lithosphere and the underlying asthenosphere; it is partly accommodated by recovery of elastic deformation, but also by the development of permanent strain, largely manifested in fault and fracture propagation. These processes are important in the assessment of post-closure GDF safety. This lithospheric recovery is one aspect of GIA and is termed post-glacial rebound (PGR); it is considered by many researchers as the principal agent of uplift in former glaciated regions [256, 257].

Evidence for Post-glacial rebound in the UK

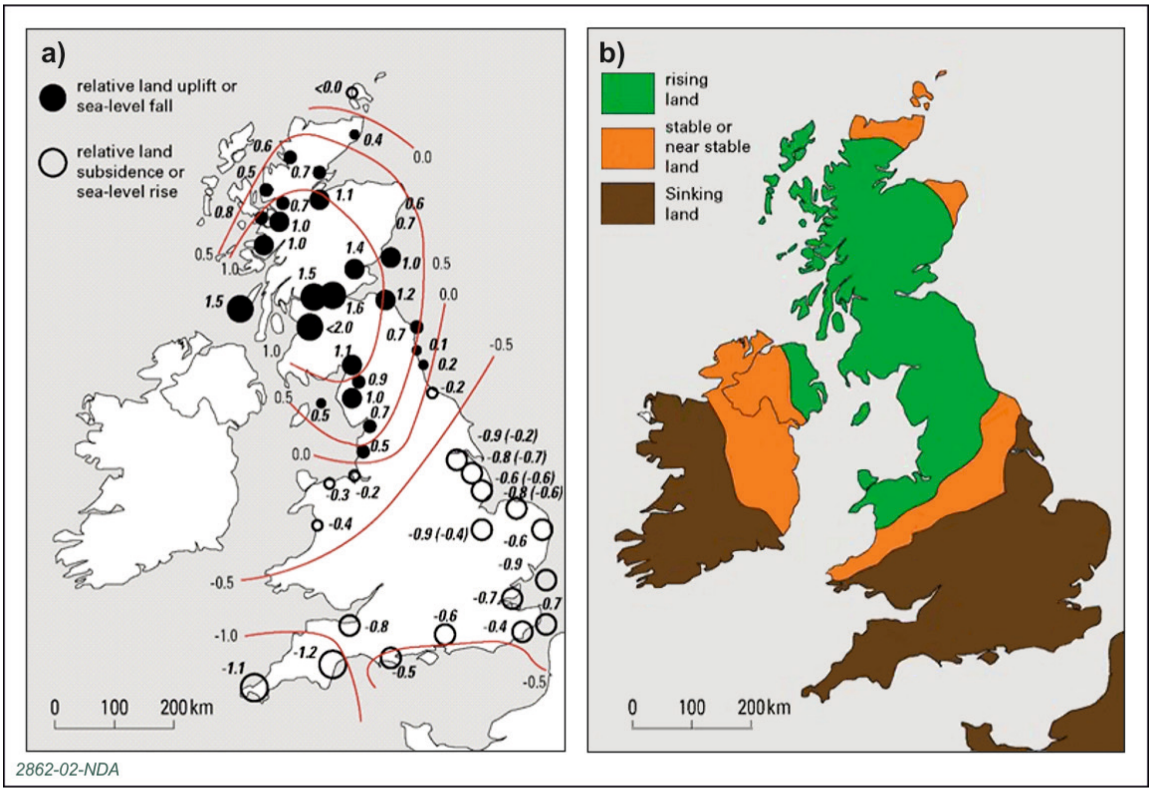
Rates of vertical movement associated with PGR have been assessed by interpretation of relative sea-level[11] and lake shoreline changes, gravity measurements, and more recently direct observations of on-going movement using space geodetic data (for example the BIFROST GPS network monitoring present-day uplift motion in northern Europe [256]).

Much of the evidence from the UK is based on measurement of changing shoreline height. Here, vastly contrasting relative sea-level changes have been recorded at different locations [258], with highest uplift of up to ca. 1.6 mm yr^{-1} centred around the area of central and northwest Scotland where it is estimated that the greatest thickness of ice was developed [259, 260]. In contrast, relative land subsidence of up to 5 cm per century has been observed in the south and east of England, with a maximum in southwest England of ca. 1.2 mm yr^{-1} [258] (Figure 24).

[11] Note that if the crust is locally depressed, due to, for example, pervious ice loading, the sea level may appear a lot higher than it actually would be relative to modern ordnance datum.

Figure 24 Estimates of PGR and present day crustal deformation in Great Britain.

(a) Late Holocene relative land-/sea-level changes (mm yr^{-1}) in Great Britain; positive values indicate relative land uplift or sea-level fall, negative values are relative land subsidence or sea-level rise. Figures in parentheses are the trends that take into account modelled changes in tidal range during the Holocene (after and based upon [258]).
(b) Green shows land which is rising as a result of post-glacial rebound, orange shows stable or near stable conditions and brown shows land which is sinking. Comparisons of estimates of rates of uplift and subsidence in the UK between continuous GPS measurements and predictions from GIA models show a good correlation ([261]).



(b) Sea-level change and impact on the GDF

Sea-level changes have occurred throughout the Earth's history and their magnitude and timing are extremely variable [262]. In the time frame relevant to the deep underground disposal of radioactive waste, eustatic changes will principally be a consequence of thermal expansion and contraction of water in the oceans as a result of climate variations, and also to the extraction of water from the oceans during ice sheet growth and its return during ice sheet melting [262]. In regions where glaciation is likely to occur, such as northern and central parts of the UK, the interactions of global sea level changes and isostatic effects can lead to complex patterns of regional sea level variations, with the result that sea level will fluctuate substantially above and below that observed at the present day [262].

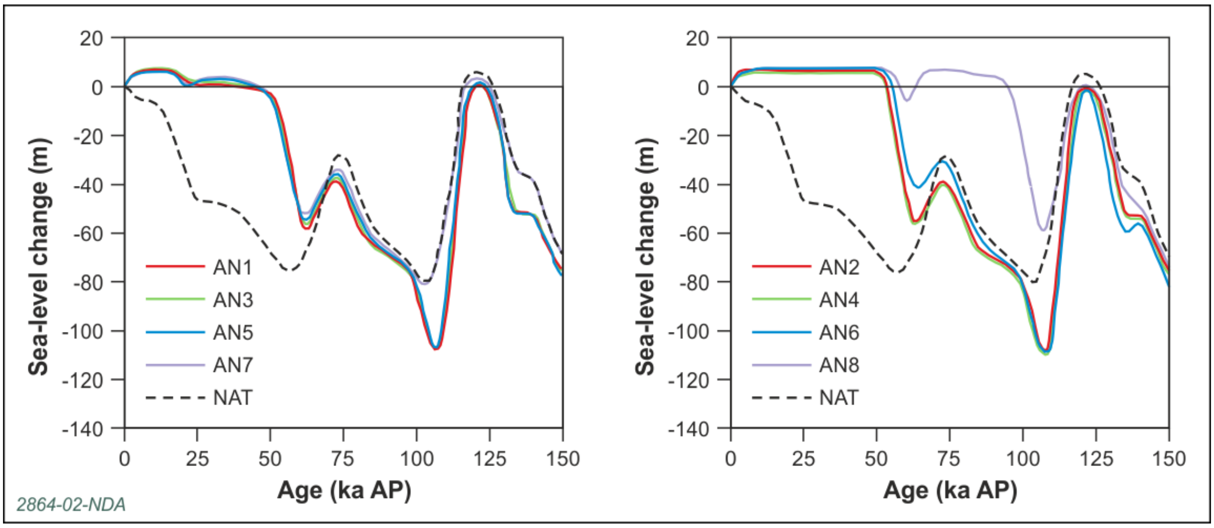
Evidence of high sea-levels in the UK, during past interglacial periods, although fragmentary, indicates that relative sea-levels higher than at present occurred in the coastal areas of the UK during the interglacial episodes that followed the Anglian (OIS 12) glaciation, with local levels more than 30 m above present levels [263]. The most compelling evidence of low relative sea-levels during the onset of The Main Late

Devensian glaciation is provided by imagery of the sea bed of the northern sector of the North Sea, where landforms such as moraines, glacial drainage and esker ridges, typical of terrestrial glacial environments, have been recognized extending to the edge of the continental shelf [224].

The modelling of long-term changes in relative sea level requires an approach that takes full account of both eustatic and isostatic effects [236]. Mechanistic models are available that represent the rheology of the Earth in terms of a rigid, elastic lithosphere and a viscous asthenosphere and these can be used with models of ice-sheet development to give a detailed picture of sea-level changes at a regional scale [236].

Future sea-level changes to 150 kyr AP have been modelled by linear regression of past sea-levels and BIOCLIM simulated ice volume under a range of climatic scenarios ranging from no anthropogenic effects to high anthropogenic CO_2 contribution (Figure 25, from [264]). For all of the CO_2 forcing scenarios, sea-level is envisaged to be above the current level for about the next 50 kyr AP, after which it drops sharply coinciding with the beginning of the modelled growth of Northern Hemisphere ice sheets. This culminates in falls of global sea-level of between c. 80-120 m at a glacial maximum that occurs between 110 and 125 kyr AP. This is followed by a rapid sea-level rise associated with widespread deglaciation. For the highest forcing scenario (AN8) the rapid fall in sea-level at c. 50 kyr AP is curtailed and only begins shortly before the glacial maximum. These models have subsequently been used to identify low-lying coastal areas around Britain that would be susceptible to future sea-level change over the next 150 kyr [265].

Figure 25 Future eustatic sea-level change (m) for low (AN1, 3, 5, 7) CO_2 forcing scenarios and the natural (NAT) simulation. b) high CO_2 forcing (AN 2, 4, 6, 8) ([264]). "High" and "low" scenarios used were those of [266]. The different scenarios assumed that the anthropogenic effects tailed off at 30 (AN1 & 2), 50 (AN3 & 4),100 (AN5 & 6) and 150 kyr AP(AN7 & 8). NAT assumes no anthropogenic effect.



Impacts on the GDF

Section 3.3.3 previously discussed reasons for groundwater flow at depth being out of equilibrium with current conditions in the near-surface. Once a UK GDF is sited and closed, subsequent changes of relative sea-level during glacial and interglacial stages could mean that the site is further from, or nearer to the coast, or even beneath the sea bed. This may lead to erosion or deposition around the surface or very shallow parts of the GDF and is likely to change the groundwater flow paths and reduce groundwater driving heads, which could result in a reduction in the rate of groundwater movement at GDF depth. Sea-level rise is a relevant issue for consideration during the active phases of GDF construction, waste emplacement and closure over a circa. 150 year lifetime, especially so if a coastal location is selected.

(c) Impact of permafrost on post-closure safety of a UK GDF

What is permafrost?

Permafrost is defined as ground that is 'permanently frozen, or that remains below freezing temperature for two or more years (as defined by the International Permafrost Association [267]). Permafrost originates at the ground's surface and grows downwards, and the primary factors governing its development are the surface temperature, the thermal capacity of the geological strata and the local geothermal gradient [268]. Surface temperature is influenced by climate, vegetation and snow/ice cover, soil characteristics and water bodies [269]. The overlying presence of glacier ice can act to insulate the ground from extreme air temperatures and prevent the development of permafrost or cause permafrost to decay. In addition, the presence of an overlying glacier can serve to increase the subglacial groundwater pressure by around two orders of magnitude, so that the freezing point can decrease to such a degree that the subglacial ground is kept unfrozen [270, 271, 272].

Permafrost forms predominantly in periglacial[12] and proglacial[13] environments under sub-arctic to polar tundra climates (Table 3). Generally, a glaciation event is preceded by tundra conditions and permafrost. A wedge of permafrost is expected to exist beneath the margin of an advancing ice sheet, but to melt as the ice sheet advances over it [273]. Permafrost may also develop during deglaciation. Today, 25% of the Earth's land area is underlain by permafrost and most modern-day periglacial environments are largely, but not exclusively, restricted to high-latitude regions [274]. Permafrost occurs to a lesser extent at lower latitudes at high altitudes, where it is known as Alpine permafrost.

Table 3 Classification scheme used to describe climate states. Table based on [275].

Climate Group	Monthly Temperatures	Climates	Notes
Sub-tropical	Over 17 ºC in all months	Subtropical rain Subtropical summer rain Subtropical winter rain	Mediterranean-type climates
Temperate	Over 9 ºC in 8 to 12 months	Temperate oceanic Temperate continental	Present-day UK climate
Sub-arctic	Over 9 ºC in 1 to 3 months	Subarctic oceanic Subarctic continental	Boreal Periglacial forest tundra
Polar	Over 9 ºC no months	Tundra Ice	Periglacial (permafrost) Full glacial

In those parts of the world currently experiencing permafrost conditions, such as parts of Siberia, it is known to penetrate to depths of 1000 m [276] (see Table 4). However,

12 Relating to or denoting an area adjacent to a glacier or ice sheet or otherwise subject to repeated freezing and thawing.

13 Applying to the land between a glacier and adjacent high ground.

Siberian permafrost is very old, dating back over two million years. Continuous permafrost of over 500 m depth requires tens or even hundreds of thousands of years to develop, so predicting future permafrost growth (maximum depth) requires a knowledge of the duration when the ground temperature remains below zero [277]. Depth to which permafrost can form is a function of the heat balance, thermal conditions at the surface and within the ground, and the geothermal heat flux from the Earth's interior [277]. Modelling of permafrost depths at Prudhoe Bay, Alaska showed that permafrost can extend to 600 m within 50,000 years at surface temperatures only slightly lower than today (~-10 degrees) [278]. In Northern Canada, permafrost reaches to depths of 500-700 m [279], while in northern Sweden discontinuous permafrost (defined as zones of permafrost with numerous scattered small thawed areas) is reported to be 100-350 m thick at an altitude of 1500 m above sea level [280]. The Swedish waste management organisation, SKB, has modelled the impact of future climate changes on bedrock temperatures in Sweden [281] and calculated that permafrost could extend to a depth of up to about 250 m during a future glaciation.

Table 4 Review of permafrost depths in a variety of alpine and polar locations.

Location	Depth of Permafrost (m)	Source
Finland (29 Locations)	Max 100, 10-50 mainly	[282]
Svalbard Coastal regions	<100	[283]
Svalbard	220	[280]
Southern Sweden	350	[280]
Svalbard Highlands	500	[283]
Lupin Mine, Nunavut, Canada	550-570	[284]
High Arctic islands, Canada	600	[285]
Northern Siberia	1000	[276]

Past climatic states and evidence of permafrost in the UK

During the LGM, continuous permafrost covered a much greater area than it does today, blanketing northern Europe and parts of central Europe, including northern, central and other mountainous areas of France, the mountains of Spain and Italy across to southeastern Hungary [286]. Available information from sites studied in NW Europe yields little quantitative evidence of past permafrost activity, whether geological, hydrogeological or hydrochemical. However, various completed or ongoing projects have, in one way or another, addressed some of the key questions relating to permafrost development and studies have also been conducted in sites presently experiencing permafrost conditions (for example, sites in Canada, Greenland and Russia) as natural analogues [284, 287]. Surface and near-surface evidence for the development of permafrost during the Pleistocene cold stages is widespread throughout Britain [208, 288, 289, 290, 291]. However, despite being widely preserved in the geological record, there is no known evidence for thicknesses of permafrost in Britain beyond several tens of metres.

Future permafrost development in the UK and at other proposed GDF sites

In the future, glacial periods in Britain are likely to result in a more continental (drier and colder) climate linked to the 'switching off' of the North Atlantic current, which would lead to the establishment of stable anticyclonic air masses over Britain that draw-in easterly polar air masses [270]. Modelling of previous glacial cycles suggests that maritime climates became re-established relatively quickly during the early parts of temperate stages and their climatic optima would have been far too warm to support deep permafrost.

1D thermal conduction modelling of the 0ºC isotherm has recently been undertaken [270] to obtain an initial overview of the possible depths of permafrost over Great Britain. The modelling was undertaken for 10 locations (Table 5) with the temperature histories from the LGM used as a proxy for future climate over the next 1 My AP. Two models were run: an average estimate case considered to be representative of conditions during the LGM; and a cold (severe) estimate case that defines the coldest temperatures that might occur in a future glacial cycle. The modelling predicted maximum permafrost depths of tens of metres using temperatures representative of the LGM, as opposed to the hundreds of metres observed for the cold estimate climate case.

Table 5 Maximum modelled depths of permafrost at the ten locations resulting from the average and cold estimate climates.[14]

Location	Maximum depth of permafrost (m) due to average estimate climate	Maximum depth of permafrost (m) due to cold estimate climate
Dartmoor	80	220
Weald	65	245
East Anglia	65	245
South Midlands	30	180
Mid-Wales	105	215
South Yorkshire	90	180
Stainmore Trough	20	205
Southern Uplands	150	305
Midland Valley	110	215
Northwest Highlands	180	235

Similar studies have been carried out internationally, at sites related to the programmes of other waste management organisations. For the Belgian site at Mol, modelling the impact of permafrost on the succession of sandstones and mudstones comprising the geological environment produced maximum permafrost thicknesses (defined as the 0 °C isotherm combined with 50% frozen ground) of 160 m and 215 m, with and without glacial surface cover respectively [292]. Results of numerical simulations of depth of permafrost formation reported in [293] in relation to a site near Olkiluoto suggest a stationary permafrost level is reached after ~140 kyr at -317.5 m. This depth is comparable with the cold climate modelling reported in [270] for South Yorkshire, the Stainmore Trough and the Midland Valley (where sandstone and mudstone also occur) that predict maximum permafrost depths of between 180 and 215 m. The proposed Forsmark site in Sweden is in crystalline bedrock and the maximum modelled permafrost depths (0 ºC isotherm) are 260 m for the repetition of the last glacial cycle and 390 m for the severe permafrost case [269]. The Dartmoor site in the UK is analogous and maximum permafrost depths of 80 to 180 m for the average climate case and 220 to 305 m for the cold estimate climate have been modelled [270, 271].

Impacts of permafrost on the GDF

[14] As noted in [16], current work to develop the UK GDF relates to England, Wales and Northern Ireland only. Some of the 10 sites in this Table are in Scotland and although permafrost information is presented for these sites, there is no implication that the GDF will be developed in Scotland.

A return to cold conditions in the UK over the next 1 Myr will result in some geographical locations experiencing permafrost conditions. In most of these areas permafrost will be followed eventually by periods characterised by a thick ice cover, and the underlying permafrost layer will gradually diminish. For considerable periods of time, when global climate conditions are colder than the present day, areas of the UK will remain ice-free and therefore, without the insulating influence of an ice cover, permafrost will develop. Because periods of permafrost can be expected in the UK, permafrost will be one of the few important environmental considerations for long-term GDF safety and performance.

If permafrost were to extend to the depth of the GDF it could affect its engineered barrier system (that is, the clay and cement-based backfill/buffer materials that, in combination with the geological barrier, contribute to the containment and isolation of disposed waste). Even if the GDF depth is greater than the zone likely to be directly affected by permafrost development, impacts on the host rock and indirect effects such as brine formation and migration (due to permafrost development at shallower depths), intrusion of freshwater from melting permafrost or gas hydrate (formed beneath the permafrost layer [294]), or cryogenic pore-pressure changes (associated with volume change during the water-ice phase transition) may affect the integrity of the geological barrier.

At shallower depths, permafrost development could affect the hydrogeological properties of lower strength sedimentary rocks, potentially affecting groundwater recharge and discharge. Frozen ground will create barriers to groundwater flow but, once thawed, permeability may be increased, leading to temporary or permanent changes to groundwater flow paths. If the Engineered Barrier System buffer or backfill of the GDF were to freeze under permafrost conditions, this would imply that there is a mechanical load on the surrounding rock [295]. Reference [296] suggests that permafrost depth rarely exceeds 500 m, so that a UK GDF will be unlikely to freeze in an environment with a thermal regime of 30 °C km^{-1} (the average UK geothermal gradient is 26 °C km^{-1}, but locally it can exceed 35 °C km^{-1} [297]. However, GDF features within the permafrost zone, such as backfilled tunnels, shafts and associated materials, such as cements within the freezing zone, could be affected (this will be considered as part of a new PhD project that is aimed to commence in late 2016, see Task 343 [11]).

(d) Glacial and subglacial erosion and impact on the GDF

During stable climatic conditions surface landscape changes are often slow and reasonably predictable, such as interglacial fluvial incision into till deposits which occur in lowland Britain [298]. However, during periods of climate change, alterations in the landscape may be both fast and unpredictable, especially in the very active hydrological regime that occurs at the margin of a retreating ice sheet where complex sequences of river terraces may be formed [299].

Erosion and associated deposition by glacial action have a substantial effect on landform. For example, ice advance during a single glacial episode in northern Britain has typically resulted in removal of most of the pre-existing unconsolidated material. In retreat, the ice has then eroded, on average, some 20 m of the underlying parent material to create a new cover of sediment [298]. The greatest depths of weathering or erosion processes occurring at or near the Earth's surface, including subsurface weathering and associated processes which affect ground or surface water movement, are likely to be caused by glaciation. For example, whereas denudation rates of most hard rock types under non-orogenic conditions are likely to be well below 50 m Myr^{-1} [261, Table 5] and river incision rates in the UK have been measured up to a maximum of 160 m for the Thames River over the total duration of the Quaternary (about 65 m Myr^{-1}), over-deepening of glacial troughs can extend to around 200 m [300].

In upland areas, ice streams can erode channels with parabolic cross sections (troughs and fjords) up to depths of 2 km [301]. Glacial over-deepening, a characteristic of valleys previously occupied by glaciers, can create valleys deep enough to potentially affect the

GDF or the backfilled infrastructure if sited at the shallow end of the proposed depth range of 200 to 1000 m; Glen Avon, a 200 m deep glacial trough in Scotland, is such an example [302]; the Sound of Raasay, a glacially over-deepened fjord, extends to 324 m below OD [303]. In lowland areas, such as Norfolk, buried valleys are known to have reached a depth of 100 m, and it has been suggested that they were formed by sub-glacial streams incising into the Chalk [304]. The existence of buried valleys, both on- and off-shore, demonstrates the depths to which glacial meltwater erosion can occur. In some circumstances the depth of these valleys is within the minimum depth (200 m) for the GDF. However, the high rates of erosion are likely to be controlled by the location of existing valleys and eventual depths will depend on factors such as ice thickness and sea level. Erosion rates need to be considered as part of the GDF siting process, although the likelihood of surface erosion being a key issue in the post-closure behaviour of the GDF can be mitigated by avoiding features such as the location of existing valleys and glacial troughs.

River incision, resulting from the isostatic change in the UK after glacial re-adjustment, has been found to reach around 160 m in the Thames river system over the duration of the Quaternary (2.6 Ma) [300]. The greatest eroding forces are those connected with the presence of ice sheets and glaciers. Infrastructure associated with the GDF in the near surface environment, such as backfilled access shafts and drifts, could therefore be affected by erosion processes. Although the GDF itself would not be impacted by this degree of erosion (due to its depth), incision / other erosional process occurring directly above it could result in the thickness of cover rock being reduced.

Rocks that dissolve easily, such as limestones, halite and gypsum, have potentially much greater erosion rates when exposed to groundwater. Water-rock interactions, including chemical weathering, have the potential to alter groundwater pathways by enhancing the dissolution or deposition of minerals. Evidence from analysis of fracture fills and groundwater chemistry shows that from relatively shallow depths, and certainly at a depth of 200 m from the surface to greater depths, the rock mass effectively buffers deeper groundwater so that it remains reducing (see Section 3.3.2). Overall, changes to the groundwater flow pathways as a result of weathering processes are likely to occur within the shallow part of a groundwater system, but will have little effect on the GDF at depth.

4.4 Summary of impacts of large-scale Earth and climate-related processes on a UK GDF

A number of large-scale Earth and climate-related processes could have an effect on the GDF in the UK.

This section has identified a number of processes where the related effects on a UK GDF and the likelihood of significant consequences have been considered and assessed. These are summarised in Table 6.

Table 6 Future natural change events and their potential to affect the GDF in the UK

Drivers	Processes	Impact on the GDF if facility directly affected. Typical depth of 600 m assumed	Likelihood of occurrence somewhere in the UK in next 1 Ma	Comments
External: climatic drivers	Glacial isostatic adjustment	Minimal	Highly probable	Any increase in seismicity will occur along existing faults.
	Permafrost	Moderate to minimal	Highly probable	Impact depends on depth of the GDF and depth of ground freezing.
	Glacial erosion	Minor to none	Highly probable	Only the GDF close to the minimum 200 m depth could be directly affected. Upland areas likely to be affected greater than lowland and will exploit existing valleys.
	Sub-glacial fluvial erosion and stream incision	Minor to none	Highly probable	Only the GDF close to the minimum 200 m depth could be affected. Upland areas likely to be affected greater than lowland.
	Sea-level rise and fall	Minimal to minor	Highly probable	Lower lying areas only, likely to change groundwater flow paths as base levels change. Sea-level fall will have a greater impact in shallow coastal areas than arise as a result of erosion potential.
	Erosion (land mass lowering)	Minor to none	Definite	Highest rates likely to be associated with existing glaciated valleys; these areas can be avoided for the siting of the GDF.
Internal: mantle convection	Earthquake induced rupture (faulting)	Minimal to minor	Probable	Earthquakes will be focussed on pre-existing faults and their location should be considered when siting. Size and magnitude of earthquakes are likely to be low and GDF structure should be designed to tolerate expected fault displacements for larger British earthquakes (~ cm's) where they are cut by potentially active faults.
	Earthquake induced vibration	Minimal	Probable	Size and magnitude of earthquakes are likely to be low and vibration hazard is significantly less than would be observed at surface. Relevance for a UK GDF is therefore low as any related implications are irrelevant in terms of the functionality of the GDF.
	Earthquake induced secondary hazards: hydrological changes	Minimal	Probable	Groundwater movement associated with earthquakes is highly improbable and relevance for a UK GDF is low as any related implications are irrelevant in terms of the functionality of the GDF.
	Subsidence	Minimal	Probable	Increase isolation of the GDF.
	Uplift and erosion	Minimal	Probable	Erosion likely to be shallow (< 200 m), impacting shallow infrastructure.
	Volcanism	Major	Implausible	No volcanic activity over the last 55 Myr, and our understanding of tectonics in the vicinity of the UK, makes it highly improbable to occur over next 10's Myr, given UK context, and implausible over the next one million years.

5 Examples of illustrative geological environments for RWM's generic DSSC studies

5.1 Introduction

We have developed six illustrative geological environments which collectively cover many of the geological and hydrogeological characteristics that are relevant to the majority of England, Wales and Northern Ireland. The UK GDF siting programme will not be bound to locate a site that maps onto these illustrative geological environments however. The six illustrative geological environments consider examples of the GDF hosted in higher strength rock, hosted in lower strength sedimentary rock and hosted in an evaporite, with a range of cover rocks.

The objective of this section is to describe, at a high level, some of the geological and hydrogeological characteristics and data that need to be considered when planning site investigations, developing disposal concepts and designs and developing safety cases.

Section 3 discussed a range of geological materials relevant to England, Wales and Northern Ireland which were described and illustrated with reference to example formations from the geological record. On the basis of Section 3, the current section presents qualitative descriptions of six illustrative geological environments that we have used to support the update to the generic DSSC. Our understanding of rock formations, as introduced in Section 3, has been utilised to derive 'building block components' for these illustrative geological environments.

As the environments described here are intended to be generic, they are described in terms of a series of generic rock types and generic structures/characteristics that are combined in different ways to create the environments. These generic building blocks, and other considerations that apply to all of the environments, are described in Section 5.2. Sections 5.3 to 5.8 then describe the six environments.

Each of the environments described in Sections 5.3 to 5.8 is illustrated with a schematic diagram that shows the typical geometry of the rock units and provides an indication of the spatial scale that might need to be considered. Indicative ranges are given for the possible thicknesses of the different units, noting that a lower thickness of zero indicates that the unit might not be present and that the diagrams are purely illustrative, so there may be more sedimentary rock units in the cover sequence than are shown.

The vertical scale of the diagram covers the expected range of depths at which the GDF might be constructed, based on current guidance (a depth of between 200 m and 1000 m below the ground surface). The horizontal scale indicates the order of magnitude of the lateral dimensions that might need to be considered, for example when planning a site investigation or when considering potential pathways between the GDF and possible discharge locations.

Further consideration of geological parameters as relevant to illustrative geological environments is provided in [305].

The Data Report [10] presents conceptualisations of groundwater flow for a higher strength host rock overlain by higher permeability sedimentary rocks, and a for a lower strength sedimentary host rock overlain by sedimentary sequence with variable permeability. These conceptualisations build on the illustrative geological environments discussed in the current report, and are further considered in the generic Environmental Safety Case [12].

5.2 Elements common to all illustrative geological environments

Although the six generic environments are likely to exhibit all the key characteristics that may need to be considered, potential candidate sites will likely show characteristics intermediate between two or more of the generic environments.

5.2.1 Context

The six generic environments described represent a range of geological conditions which could plausibly occur England, Wales and Northern Ireland. Each generic environment has differing properties in terms of rock types present, structure, faulting and heterogeneity, hydrogeology and hydrochemistry.

The geographical area considered in this work is England, Wales and Northern Ireland, including sites that extend for up to 20 km offshore. Consistent with their intended purpose, the environments are generic and do not represent specific localities. However, all of the environments described herein could plausibly be found within the area of interest, although the specific environments described are not necessarily common.

At the present generic stage of investigations all environments are to be treated as being equally plausible. Consistent with this approach, the environments are named rather than being numbered. In practice, many potential candidate sites within the area of interest would have characteristics intermediate between those of the environments described here. Furthermore, the characteristics may vary laterally within the area that would need to be considered when developing the GDF, for example the cover sequence might change laterally from being dominated by higher permeability sedimentary formations to being dominated by lower permeability sedimentary formations. It is considered unlikely that the environment in a potential site would fall outside those illustrated by the six environments described herein. Collectively the described generic environments are likely to exhibit all the major characteristics that might need to be considered for any actual environment that might be selected.

The descriptions of the environments presented in this section are all present day “snap-shots” and imply nothing about the likely temporal variability of the environment over the million year timescale considered in the post-closure safety case. It should be noted that a particular type of environment in different geographical locations may evolve with significant differences. For example, the north of England may in the future be glaciated, whereas the south of England may remain ice-free, and this may have a significant impact on parameters such as in-situ stress, groundwater head and groundwater chemistry.

Conditions (such as stress state, groundwater chemistry and head) at depth, especially in low permeability strata, tend to evolve more slowly than conditions at the surface, even when considering the long timescales associated with processes such as glacial cycles or even tectonics. It is therefore likely that conditions at depth will not be in equilibrium with surface conditions for any of the environments that are described herein and instead reflect the history of the site. In the generic case, there is thus significant uncertainty in the conditions expected at depth at the present day because these include a history component, which varies with location rather than environment type, and are not simply determined by the physical and chemical properties of the rocks. Assessing the likely future evolution of a site is further complicated by uncertainties in future evolution of conditions at the surface.

5.2.2 Illustrative geological environments - rock types

There are a number of rock types present in all the geological environments, including the host rock, the cover rocks and the superficial deposits. Sedimentary rocks that are not the host rock have been divided into 'higher permeability sedimentary formations' and 'lower permeability sedimentary formations'.

Definitions for higher strength rock, lower strength sedimentary rock and evaporite are provided in Section 2.

In addition to the host rock it is necessary to consider the cover sequence, if any, that overlies the host rock and, for some environments, the underlying rock units. In this report these rocks have been defined primarily in terms of their hydrogeological properties.

A formation is a sequence of rock layers with distinctive characteristics. Sedimentary rocks are divided into formations, and although their thicknesses are very variable, each formation can be shown on a geological map at 1:50,000 scale. The rocks in a formation have characteristics that distinguish it from the adjacent formations, but are not necessarily homogeneous; a formation may be defined by a distinctive grouping of a range of rock types. For the purposes of this section, sedimentary rocks that are not the host rock have been divided into:

- higher permeability sedimentary formations. These are rocks with sufficient permeability that they would be capable of supporting groundwater flow and advective mass transport (for example, solute, colloid and possibly particulate transport) if sufficient driving head was available. This flow could be dominantly through discontinuities, or through the matrix, or through a combination of the two. Typical rocks in this category include sandstone, limestone and Chalk. The category includes aquifers, but also includes rocks in which the permeability is not high enough for them to be exploited as water sources (the definition of an aquifer). Minor lower permeability layers within a formation dominated by higher permeability rocks may result in anisotropy in the permeability.
- lower permeability sedimentary formations. These are rocks in which the permeability is so low that only diffusive mass transport can occur; driving head gradients sufficient to fracture the rock would be required to generate advective flow. Typical rocks in this category include mudstones and siltstones and other clay-rich rocks, as well as evaporites (including some evaporite-rich formations not judged suitable as an evaporite host rock). The category also includes low permeability limestones such as certain beds within the Chalk. There may also be minor beds of higher permeability rock within a lower permeability formation. These rocks act as aquitards and may act to confine higher permeability rocks.

Superficial deposits within the UK are generally the result of recent (glacial or post-glacial) processes. While there is some relationship with the underlying rocks, their nature and properties are often largely determined by location, rather than the geological environment. They range from highly permeable sands and gravels to low permeability tills and clays. These superficial deposits may also include highly weathered, and hence potentially permeable, portions of the underlying rock unit. Similarly, their thickness varies with location from virtually nothing to tens or more than a hundred metres thick. The nature of the superficial deposits is important because they influence the pattern and amount of recharge to the deeper hydrogeological system and the characteristics of any discharges (diffuse or focussed, and the degree of mixing with 'surface' water). Superficial deposits are therefore marked on the schematic diagrams, but they are not discussed in detail because of their dependence on specific location.

It is also noted that superficial deposits in the UK are diverse in nature. The processes that create them (river migration, glaciation, etc.) tend to be of relatively small scale compared with the basin-wide processes that lay down sedimentary formations. The superficial deposits are therefore likely to be more heterogeneous than the underlying rocks, with significant variations in properties on length-scales of tens to hundreds of metres.

5.2.3 Illustrative geological environment - hydrogeology

Groundwater movement through the environment will depend largely on the hydrogeological properties of the host rocks and cover rocks. In higher strength rocks groundwater movement will predominantly be through inter-connected fractures, whereas in lower strength sedimentary rocks movement will be dominated by diffusion. In evaporite, permeability would be sufficiently low there would be no significant groundwater flow.

The overall hydraulic conductivity of a higher strength host rock body will be determined by the frequency, inter-connectivity and transmissivity of the discontinuities. Any groundwater flow that occurs through a higher strength host rock will be through these discontinuities; the hydraulic conductivity of the rock matrix will be very low and any water or solute transport will be dominated by diffusion. The transmissivity of the discontinuities will depend upon their aperture, their orientation relative to the in situ stress field and the nature of any fracture fills or fault rocks that might be present; not all fractures or faults will contain connected porosity able to support flow.

A higher strength rock may be subdivided or compartmentalised into multiple hydrogeological domains, perhaps delineated by the larger faults or shear zones, and/or on the basis of detailed lithology. If these domains are not especially well connected the heads within adjacent zones may not be in equilibrium, with potentially large head gradients being present across boundary features such as faults or shear zones. As a result the hydrogeology of higher strength rocks may be complex.

Higher and lower permeability formations are defined on the basis of their hydrogeological properties. Higher permeability formations are able to support advective flow and mass transport if sufficient driving head is available. Flow may be through the matrix, through fractures or through a combination of the two. Some higher permeability sedimentary rock formations may be limestones or highly cemented siliciclastic rocks, through which groundwater will flow dominantly via fractures. Lower permeability formations are unable to support advective flow and thus provide a diffusion-dominated barrier that isolates lower formations from those above. The permeability may be anisotropic as a result of the interbedding of lithologies with different hydrogeological properties. This layering and anisotropy may promote sub-horizontal flow and vertical stratification of the hydrogeological system.

Halite and halite-dominated units would have a permeability that is sufficiently low to ensure that there will be no meaningful groundwater flow and all transport will be by diffusion.

5.3 Illustrative geological environments

5.3.1 Higher strength rock to surface

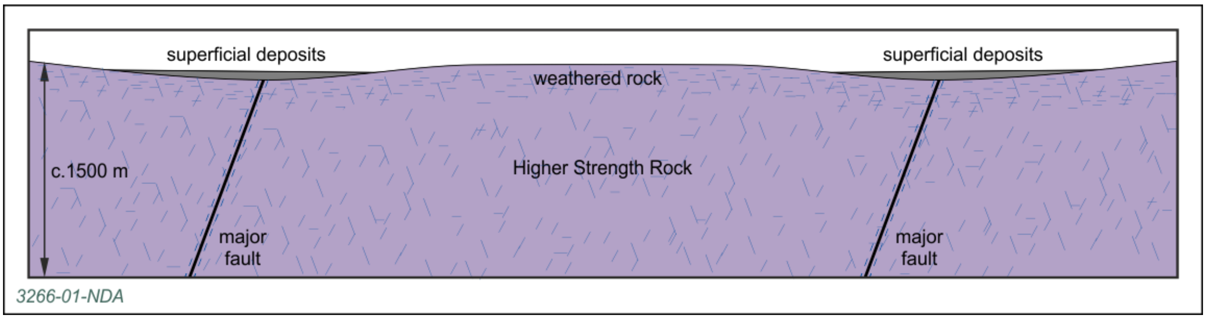
In this instance higher strength rock occurs from the proposed GDF depth to the surface. Significant complexities may remain due to discontinuities, spatial heterogeneity and a complex overburden, including highly weathered and altered higher strength rock and superficial sedimentary deposits. The hydrogeological properties of this environment depend largely on the nature of the overburden and the topographical gradients and groundwater density variations.

In this environment higher strength rock occurs throughout the depth range within which the GDF might be constructed (200 m to 1000 m). However, near to the surface the higher strength rock is likely to have been weathered to some degree (Figure 26), and potentially this weathering may have progressed sufficiently that the rock no longer has the mechanical properties of a higher strength rock. The higher strength rock will be fractured and faulted to some degree. These structures may influence the depth to which alteration extends, the higher strength rock possibly being weathered to a greater depth adjacent to fractures or faults, and some structures may have been affected by alteration in the past.

The higher strength rock body (or its uppermost weathered lower-strength zone) does not necessarily crop out at the ground surface, but could be overlain by superficial (unconsolidated) sedimentary deposits, such as glacial tills, river gravels or soils. These superficial deposits are likely to be of variable thickness and could be highly heterogeneous.

Faults and other significant structures are likely to be present and could extend throughout the entire depth range under consideration. Although this environment includes only a single rock type, the details of the structures within that rock mass will be important in determining the hydrogeological behaviour and the rock quality, and this could be a hydrogeologically and structurally complex environment.

Figure 26 Schematic of Higher strength rock to surface illustrative geological environment.



Recharge may occur directly to the higher strength rock where this is exposed at the ground surface, or via any superficial deposits that overlie the higher strength rock. Recharge to GDF depths in this environment will be controlled by a combination of factors that are related to the geographical setting and factors that are related to the geological environment itself. Important among these latter factors are the distribution and characteristics (notably thickness and permeability) of superficial deposits and the thickness of any near-surface weathered zone. If the near-surface rocks are sufficiently permeable compared with the deeper rocks, and transmissive structures do not extend to depth, then the active part of the hydrogeological system may be confined to a relatively shallow surface layer and recharge to GDF depths may be small.

Groundwater head gradients are likely to be controlled by a combination of topographical gradients and groundwater density variations, which in turn reflect the hydrogeochemistry of the surrounding region. Both of these factors will be very dependent upon the precise location of this kind of environment. One reason for the existence of some upland areas is the presence of higher strength rocks, which are relatively resistant to erosion and/or weathering.

The chemistry of the water within the higher strength rocks will depend upon the precise geological setting and geographical location of the environment. Generally, the expectation is that salinity will increase downwards from fresh water (Total Dissolved Solid (TDS) < 1000 mg/l) within a few tens to hundreds of metres from the surface. In contrast to the recharge zone, deeper waters will be reducing (anoxic) and more alkaline. The salinity will reflect mixing between different waters carrying solutes from sources outside the environment and chemical reactions within the environment. The overall level of salinity is likely to depend upon whether saline water has entered the environment from elsewhere and upon the extent to which any such water has been flushed by, or mixed with, meteoric recharge water. Chemical reactions within the higher strength rock will also modify the chemistry of water originating from outside the area to some degree. The nature of these reactions will depend upon the chemical / mineralogical characteristics of the higher strength rock.

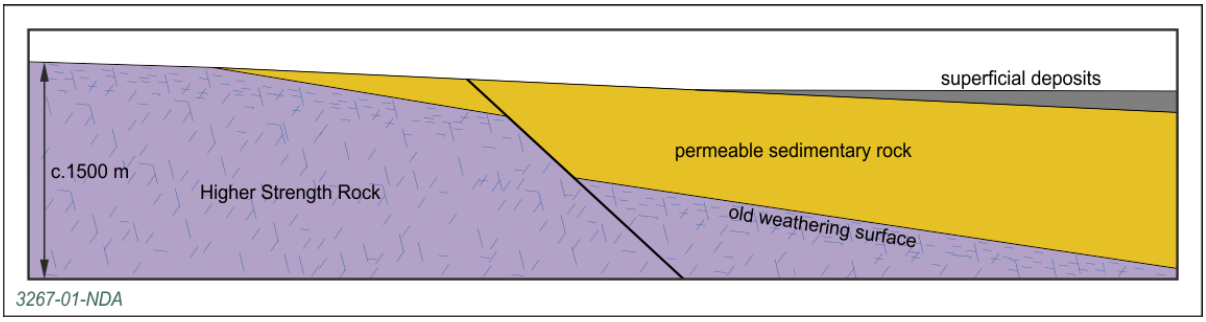
5.3.2 Higher strength rock overlain by higher permeability sedimentary rocks

In this environment a higher strength host rock is overlain by higher permeability sedimentary rocks. The thickness of the cover rock sequence is variable and in part controlled by faulting, likely thickening towards the coast. Although there may be some lower permeability formations within the sequence, these are not sufficiently extensive or thick enough to provide significant barriers to groundwater flow. Groundwater head will be controlled by the interaction of the topography and salinity gradients, which are associated with higher strength rock outcrops, causing high relief, and any saline interface associated with the coast.

This environment lies at the margin of a sedimentary basin and, in the area of interest, is likely to be sufficiently close to the coast that coastal processes may influence the nature of the groundwater flow system (Figure 27). Higher strength rocks are overlain by a cover sequence of higher permeability sedimentary rock formations. The thickness of the higher permeability sedimentary rock sequence is partly controlled by basin-margin faults which may have been active during the deposition of the precursor sediments (that is, the faults may have been ‘syn-sedimentary’). The cover sequence thickens towards the centre of the basin. There may be significant thicknesses (tens of metres) of superficial (unconsolidated) sedimentary deposits, such as glacial tills, river gravels or soils, overlying the cover sequence. These superficial deposits are likely to be of variable thickness and could be highly heterogeneous.

In this illustrative geological environment it is assumed that higher permeability sedimentary rocks generally extend to the surface; the underlying higher strength rock does however reach the surface in some places.

Figure 27 Schematic of Higher strength rock overlain by higher permeability sedimentary rocks illustrative geological environment. The GDF might be located anywhere the higher strength rock within the 200 m to 1000 m depth range.



Where it outcrops, the higher strength rock is likely to have been weathered to some degree (Figure 27). The uppermost part of the higher strength rock immediately below the sedimentary cover is also likely to show some degree of alteration owing to palaeo-weathering prior to deposition of overlying sediments. As a result, it is likely to be more permeable than deeper parts of the higher strength rock.

In at least part of the environment, recharge may be able to occur directly to the higher strength rock. However, over most of the area of the environment recharge will be to the overlying higher permeability sedimentary rocks. Superficial deposits, such as glacial deposits, river gravels and soils will influence the recharge that occurs.

Groundwater head gradients are likely to be controlled by a combination of topographical gradients and groundwater density variations, which in turn reflect the hydrogeochemistry of the adjacent basinal environment. Where the higher strength rocks outcrop, there may be relatively high relief. The surface elevation will generally decrease towards the coast. Meteoric water that recharges the groundwater will tend to flow in the direction of this topographical gradient (were groundwater to meet a fault, considerable divergence from the topographic gradient might be expected, either due to a barrier effect or by diverting flow if the fault is permeable). At depth, denser, more saline water, originating towards the centre of the adjacent sedimentary basin will tend to move in the opposite direction under the influence of the density gradient, and there will be a saline transition zone associated with the coast. Overall flow at depth will be governed by a balance between these two driving forces. The extent of the flow system that would need to be considered depends on the location of the GDF relative to any saline interface.

The chemistry of the water within both the higher strength rocks and the higher permeability sedimentary cover rocks will depend upon the degree of mixing between fresh meteoric recharge water and more saline, Na-Cl dominated water at depth. The salinity of this latter water may originate in evaporite deposits towards the centre of an adjacent sedimentary basin (not shown in Figure 27), where lower permeability formations are likely to be present, or it may simply be saline water trapped at the time of deposition, modified by water-rock interactions and mixing. The result is that at any given locality salinity increases generally downwards and at any given depth salinity increases generally towards the sedimentary basin. However, vertical salinity gradients will vary markedly from place to place. Owing to the permeability contrast there may be a relatively sharp salinity gradient between the less permeable higher strength rocks and the overlying higher permeability sedimentary rocks. At shallow levels towards the coast there will be seawater within the higher permeability sedimentary rocks.

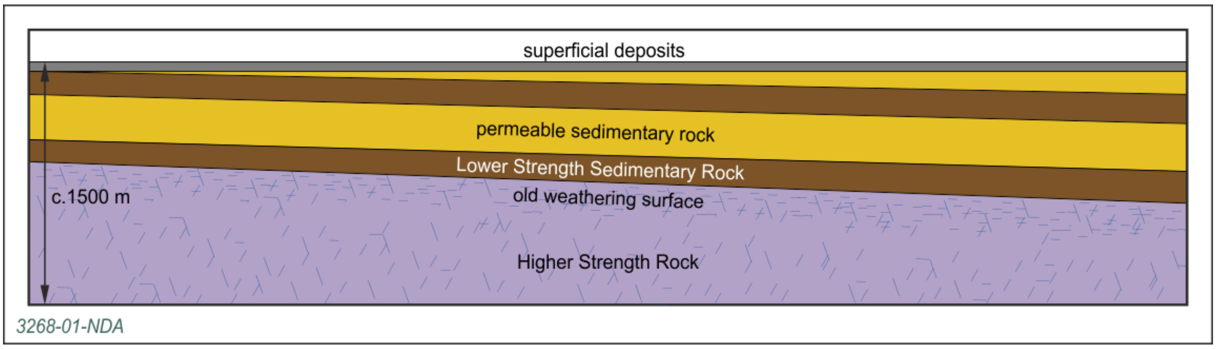
5.3.3 Higher strength rock overlain by lower permeability sedimentary rocks

This environment comprises a higher strength host rock overlain by a sequence of sedimentary cover rocks, at least one of which being of sufficiently low permeability to provide an adequate barrier to advective flow. The driving head gradients in the host rock of this environment are likely to be low, as although the host rock may have high permeability, the recharge to GDF depths would be very low.

This environment is likely to be associated with a basement high, to allow higher strength rocks to be present at suitable depths to host the GDF. In this environment, higher strength rocks at depths suitable to host the GDF are overlain by a cover sequence comprising higher and lower permeability sedimentary formations (Figure 28). Within this sequence there is at least one lower permeability formation that is of sufficient thickness and lateral extent to form a barrier to groundwater flow and isolate the higher strength rock from the surface environment. Within the area of interest, the cover sequence is also likely to include at least one higher permeability formation; the nature of UK geology is such that all potential UK locations for this environment tend to have a mixed sedimentary cover sequence. The sedimentary sequence is likely to be overlain largely by superficial (unconsolidated) sedimentary deposits, which could be of variable thickness and highly heterogeneous.

The higher strength rocks do not crop out at the ground surface anywhere within the environment. The uppermost part of the higher strength rock immediately below the sedimentary cover is likely to show some degree of alteration owing to palaeo-weathering prior to deposition of overlying sediments, and may be of higher permeability than the unweathered higher strength rock. Higher permeability formations may crop out or lie directly beneath the superficial deposits.

Figure 28 Schematic of Higher strength rock overlain by lower permeability sedimentary rocks illustrative geological environment. The GDF would be located within the higher strength rock.



The presence of a lower permeability formation between the host rock and the ground surface has the potential to isolate the host rock from the surface environment and the recharge that occurs there. However, outcropping higher permeability formations may carry significant flow to depth, depending on the geometry of the basin. Driving head gradients in the host rock may be low in the typical locations where this environment would be found; there may not be advective flow through the higher strength host rock because, while the permeability could support advection, the other hydrogeological parameters do not.

Groundwater head gradients are likely to be controlled by a combination of topographical gradients and groundwater density variations, which in turn reflect the hydrogeochemistry of adjacent areas. Meteoric water that recharges the groundwater will tend to flow in the direction of the topographical gradient and reflect local small scale topography. At depth, head gradients will be more subdued and denser; more saline water will tend to flow less rapidly. The most active part of the hydrogeological system is likely to be bounded by the uppermost lower permeability formation, although, as noted above, higher permeability formations beneath this uppermost lower permeability formation may carry significant flow if they outcrop.

Immediately below the surface, and for a depth of perhaps a few tens to hundreds of metres, the groundwater will be fresh. Water may also be relatively fresh at depth in higher permeability formations that outcrop. At greater depth the chemistry will be influenced both by the nature of the sedimentary cover (for example, whether evaporites are present in low permeability formations) and water-reactions within the environment, and possibly salinity transported by groundwater flowing from elsewhere.

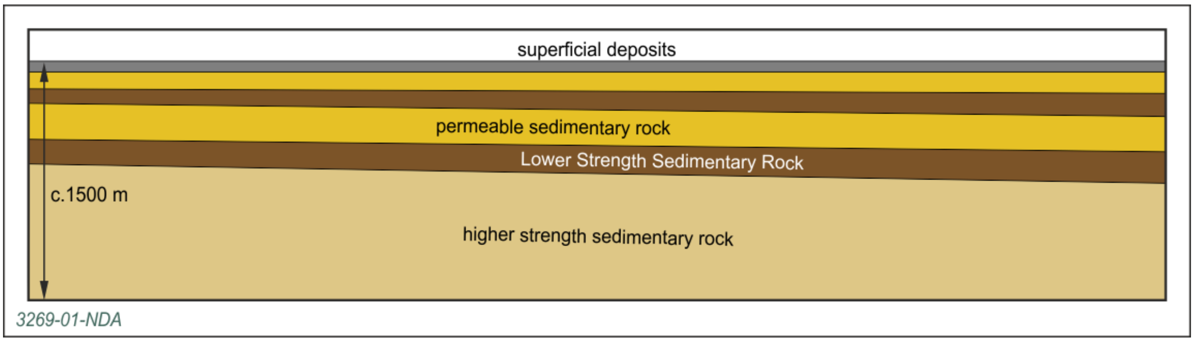
The chemistry of the water within the higher strength rocks will depend upon the conditions under which the overlying sedimentary rocks were deposited, the nature of the salinity sources outside this environment, and chemical reactions that occur within the environment. Generally, the expectation is that salinity will increase downwards from fresh water (TDS < 1000 mg/l) within a few tens to hundreds of metres from the surface. In contrast to the recharge zone, deeper waters will be reducing (anoxic) and more alkaline.

5.3.4 Lower strength rock overlain by higher permeability sedimentary rocks

In this environment a lower strength sedimentary rock is used as the host rock, and it is overlain by higher permeability sedimentary rock. It is likely that this environment is within a sedimentary basin. Recharge to GDF depths is expected to be very small as the permeability of the host rock and immediate cover rock will be very low.

This environment is likely to be set in a sedimentary basin. The host rock of interest is a lower strength sedimentary host rock that may directly overlie a higher strength rock (basement) or may be set within a sedimentary sequence (that is, it may be underlain by rocks similar to the cover sequence). In this environment the sedimentary sequence overlying the host rock is dominated by higher permeability formations (Figure 29). However, within the area of interest, the cover sequence would include at least one lower permeability formation; there do not appear to be any locations within the area of interest in which a potential lower strength sedimentary host rock is overlain only by higher permeability formations. Superficial deposits would overlie the sedimentary sequence.

Figure 29 Schematic of Lower strength rock overlain by higher permeability sedimentary rock illustrative geological environment. The GDF would be located in the lower strength sedimentary host rock formation, which may be underlain by a sedimentary sequence or by higher strength rock.



In this environment, recharge to the host rock is expected to be small due to the low permeability of the host rock. However, if the higher permeability formations outcrop, the potential exists for higher permeability formations immediately adjacent to the host rock to support significant flow. Nevertheless, the presence of the low permeability host rock and at least one low permeability formation in the cover sequence means that this flow is likely to be dominantly horizontal rather than vertical. The most active part of the hydrogeological system is likely to be confined to the units above the uppermost low permeability formation.

The chemistry of the water within the rock sequence will depend upon a combination of the salinity trapped during deposition of the sedimentary rocks, salinity sources outside this environment and chemical reactions within this environment. Evaporite beds are not likely within the lower permeability formations in this environment, so there is unlikely to be a source of salinity greater than seawater within the sequence. The overall level of salinity is therefore influenced by whether higher salinity water has entered the environment from elsewhere and upon the extent to which any such water has been flushed by, or mixed with, meteoric recharge water. Lower permeability sedimentary horizons may retain palaeo-marine porewater salinity originating in the original depositional environment. Salinity in the higher permeability formations is likely to be the same as, or lower than, that in the lower permeability formations. At depths below a few tens to hundreds of metres, groundwaters will be reducing.

5.3.5 Lower strength rock overlain by lower permeability sedimentary rocks

In this environment a lower strength sedimentary rock comprises the host rock, and this is overlain by a lower permeability sedimentary rock. This environment is likely to be within a sedimentary basin. Recharge to GDF depths is expected to be very small as the permeability of the host rock and immediate cover rock will be very low.

This environment is very similar to the one described in Section 5.6, except that the sedimentary sequence is dominated by lower permeability formations. Hence no additional illustration is provided.

This environment is likely to be set in a sedimentary basin. The host rock of interest is a lower strength sedimentary host rock that may directly overlie a higher strength rock (basement) or may be set within a sedimentary sequence (that is, it may be underlain by rocks similar to the cover sequence). In this environment the sedimentary sequence overlying the host rock is dominated by lower permeability formations. However, within the area of interest the cover sequence would include at least one higher permeability formation; there do not appear to be any locations within the area of interest in which a potential lower strength sedimentary host rock is overlain only by lower permeability formations. Superficial deposits would overlie the sedimentary sequence.

In this environment, recharge to the host rock is expected to be small due to the low permeability of the host rock and the fact that it is situated within a dominantly low permeability sequence. However, if the higher permeability formations outcrop, the potential exists for them to support significant flow. The dominance of low permeability formations means that this flow is likely to be confined and dominantly sub-horizontal. The most active part of the hydrogeological system is likely to be confined to the units above the uppermost low permeability formation, and would potentially be confined to the superficial deposits.

The chemistry of the water within the rock sequence will depend upon a combination of the salinity trapped during deposition of the sedimentary rocks, salinity sources outside this environment and chemical reactions and mixing/flushing occurring within this environment. Evaporite beds may be present within the lower permeability formations in the cover sequence and would provide a source of salinity greater than seawater within the sequence. There is therefore the potential for highly saline water to be present at depth, including within the host rock.

Groundwater at depth is therefore likely to be saline within the lower permeability units and may be brine if they include evaporite beds (see Table 2-3 of [305] for further information relating to model water compositions specified to describe water chemistry). There may be sharp salinity contrasts between lower-permeability formations and any higher permeability formations. In the higher permeability formations salinity may be higher or lower than in the lower permeability formations; although if there is active advection through these higher permeability formations the salinity within them is likely to be relatively low. At depths below a few tens to hundreds of metres, groundwaters will be reducing.

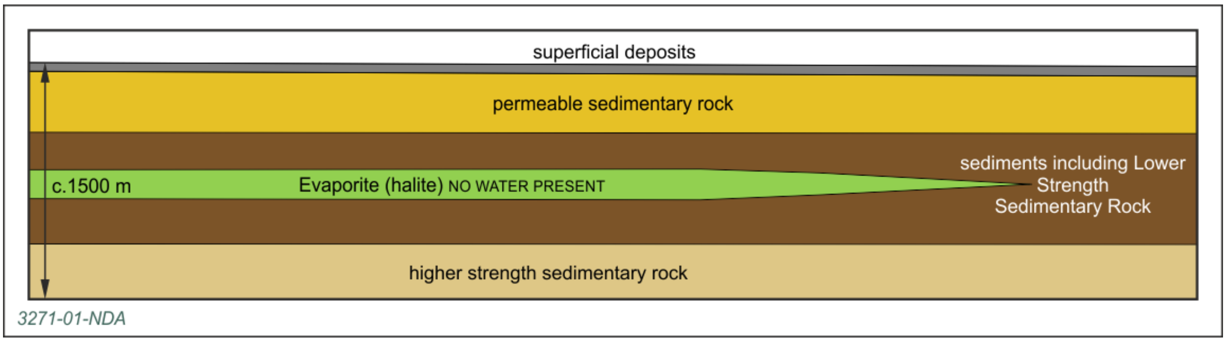
5.3.6 Evaporite overlain by a sedimentary sequence

In this environment a host rock is comprised of halite within an adjacent sequence of lower permeability sedimentary rocks. This environment would be found within a sedimentary basin. The low permeability formations adjacent to the host rock prevent recharge from reaching the evaporite, hence it has been preserved. There could be significant groundwater movement in overlying higher permeability formations, but this would be prevented from reaching the host rock by the adjacent low permeability strata.

This environment is found within a sedimentary basin. The host rock in this example is a halite or halite-dominated layer within a sequence of higher and lower permeability sedimentary rocks (Figure 30). The host rock would contain some clayey interbeds and would be bounded above and below by lower permeability sedimentary formations that comprise interbedded halite and clayey units, but would not display the required creep properties to be classified as an evaporite host rock. This host rock sequence would be overlain and underlain by interbedded higher and lower permeability formations that do not contain significant halite. In the UK the actual host rock may only be a hundred metres or so thick, but the whole host rock sequence of halite and adjacent lower permeability formations could have a thickness of several hundred metres.

The evaporite host rock would occur within a sedimentary basin so the dip of the units would be relatively low.

Figure 30 Schematic of Evaporite overlain by a sedimentary sequence environment. The GDF would be located within the halite formation.



The low permeability formations adjacent to the host rock would prevent recharge from reaching the host rock, which is why it has been preserved. However, there could be significant flow in any higher permeability formations that overlie the host rock. Groundwater in the units below the host sequence is expected to be highly saline, so groundwater flow rates in these units are expected to be low, even if the formations have significant permeability. There may be a relatively active hydrogeological system above the uppermost higher permeability formation.

The groundwater in the host sequence, and most likely in the underlying sequence, will be Na-Cl dominated brine, with the salinity originating in the evaporite. Groundwater salinity in the overlying sequence will depend upon the precise geological setting and geographical location of the environment. The salinity will reflect the original depositional environment as well as mixing between different waters carrying solutes from sources outside the environment and chemical reactions within this environment (including dissolution of evaporites). Lower permeability sedimentary horizons may retain palaeo-marine porewater salinity originating from the original depositional environment. There may be sharp salinity contrasts between lower permeability formations and higher permeability formations in the cover sequence; in the higher permeability formations salinity may be higher or lower than in the lower permeability formations, although if there is active advection through these higher permeability formations the salinity within them is likely to be relatively low. At depths below a few tens to hundreds of metres, groundwaters are likely to be reducing.

6 GDF-induced impacts on the geosphere

The construction of the GDF will have both immediate and longer-term impacts on the geosphere. In this section we describe the nature of the perturbations caused by the GDF, dividing them into 'thermal', 'hydrogeological', 'mechanical' and 'chemical' categories. We then discuss the timescales and distances over which these perturbations may occur, and identify the most significant perturbations and combinations of perturbations for the three illustrative geological settings that we are considering. We conclude by describing our current understanding of the impact of these perturbations on the three illustrative geospheres.

THE GDF will perturb the geosphere in which it is constructed. The effects may occur over a range of timescales and length scales, and will arise as a consequence of features in the system (for example, the design of the EBS), events (for example, the excavation of a tunnel) or processes (for example, the convergence of the rocks around a tunnel). In the DSSC, a broad range of features, events and processes (FEPs) are considered, which could influence the safety of the system and the potential evolution of the GDF and its geological setting.

In this section, the types of perturbations that the GDF could cause to the geosphere are considered. To help structure the discussion, the perturbations have been categorised according to their type. This report considers thermal (T), hydrogeological (H), mechanical (M) and chemical (C) perturbations. The impacts of gas (G) are considered in detail in the Gas Status Report [6]. Couplings between these perturbations are also considered.

It is recognised that the geosphere will also impact directly on engineered components of the GDF, principally due to the inflow of groundwater. These chemical interactions will affect both the evolution of the near-field (which comprises the EBS, the waste containers and the wasteform) and the behaviour of radionuclides and other contaminants in the near field. These issues are discussed further in the Waste Package Evolution, Engineered Barrier System and Radionuclides and Non-radiological Species in Groundwater Status Reports [2, 3, 5].

6.1 Thermal perturbations (T)

Thermal perturbations arise from the materials and processes used to construct the GDF and from the presence of the wastes within it. The most significant thermal perturbation in the GDF occurs because some of the wastes themselves are heat-producing as a result of radioactive decay.

Radionuclide decay liberates energy in the form of expelled particles (usually alpha or beta particles, or neutrons), frequently accompanied by electromagnetic radiation in the form of X-rays and/or gamma rays. The subsequent absorption of these particles or radiation gives rise to an increase in the temperature of the absorbing medium. A significant amount of heat is generated by high heat generating wastes (HHGW). Depending on the irradiation history and time period of waste storage prior to disposal, this can be several hundred Watts per m^3 of packaged waste. Lower activity wastes (such as ILW/LLW) generate significantly less heat, typically a few Watts per m^3. Much of the heat generated by radioactive waste comes from the decay of short- and medium-lived fission products such as Sr-90 and Cs-137 and the medium-lived actinides Pu-238 and Am-241. The rate of heat generation decreases with time, as these relatively short-lived radionuclides decay. A low residual heat output from segregated plutonium wastes may be expected to persist for much longer timescales, because of the long half-life of the plutonium isotopes Pu-239 and Pu-240.

The basic mechanisms of heat transfer are conduction, convection and radiation. Conduction is the most significant means of heat transfer within a solid or between solid objects in thermal contact. Transfer of heat through the solid material takes place by the interactions between vibrating atoms or molecules. Consequently, conduction will be the most important mechanism for transferring heat away from the GDF after it has been sealed. Thermal convection, that is, transfer of heat within a fluid such as groundwater, does occur, but the low groundwater flow rates in the types of rocks that would be suitable for hosting the GDF make this contribution negligible [306]. Thermal radiation is unimportant in terms of heat transfer from the GDF because of the very short range of even the highest energy electromagnetic radiation in rocks.

The GDF will be designed to ensure that the temperature in the vicinity of the waste package or container does not exceed the design parameters for the disposal system. A key geosphere input to this calculation is the thermal conductivity of the rock. From knowledge of the heat-producing properties of the waste, the amount of waste to be disposed of and the thermal properties of the surrounding rocks, it is possible to develop the design and layout of the GDF. For a rock with a higher thermal conductivity:

- temperature rises in a given location due to heat-emitting waste packages are likely to be lower than in less thermally conductive rocks
- the spacing between heat-emitting waste packages can be closer than in other host rocks because the heat generated is more easily conducted away from the engineered barrier system. This may facilitate a reduced GDF footprint.

Disregarding the contribution to heat transfer from convection means that predicted temperature rises in the GDF will be overestimated, which is a conservative approach.

In order to calculate the actual temperature in the GDF, which is the parameter of interest, it is also necessary to understand the ambient temperature in the rocks at depth. The geothermal gradient (the rate at which the Earth's temperature increases with depth) can be calculated from the heat flow through the rock and the thermal conductivity of the rock. In addition, at the depths of interest, there are many direct measurements of rock temperature. In the UK, the average geothermal gradient is 26°C per kilometre and variations about this average value are well understood [307]. For example, slightly higher geothermal gradients occur in some granitic areas where the rocks have elevated concentrations of uranium and heat production in the rock is consequently slightly higher. The natural temperature conditions in the rocks at great depth are very stable, although there will be some impact of climate on rock temperatures near the surface and down to a depth of several hundred metres, see Section 4.3.3, and also potentially of palaeoclimatic conditions that historically were present [308].

The heat generated from heat-generating waste will lead to a temperature rise in the surrounding rocks. The temperature rise due to the heat generated within the GDF (and the associated displacements, strains and stresses) will be superimposed on the background temperature distribution (and the background displacements, strains and stresses). Surrounding rocks will expand as a result of the temperature rise, and this may lead to an uplift of the ground surface above the GDF. The magnitude of any uplift depends on the heat output of the waste, the design of the GDF (in particular, its footprint and depth) and key properties (the thermal conductivity, specific heat capacity, density, thermal expansion coefficient and Poisson's ratio) of the GDF materials and surrounding rocks. Variations in thermal conductivity and expansivity in the overburden, and the scope for accommodation of any expansion in the near-field by compressional accommodation in the over- and under-burden, are also important aspects affecting the magnitude of any uplift.

Cement hydration (or 'curing') results in the generation of heat through reactions such as the hydration of anhydrous Portland cement to form minerals such as calcium hydroxide and calcium silicate hydrate (CSH) gels. In the GDF that contains significant volumes of cement, for example as a mass backfill, these exothermic cement hydration reactions will produce a short-lived temperature rise of the order of months to years. The temperature rise will depend on factors such as the cement formulation and the volume of the cement that hydrates *in-situ* in the GDF; for further information see [309] and [3]. In the longer term, thermal evolution of the engineered barrier system will be dominated by the radioactive decay heat, as discussed above.

Heat would also be generated in the very unlikely event of a criticality caused by an accumulation of fissile radionuclides such as Pu-239 or U-235 in the engineered system or immediate host rock during the post-closure period in the GDF [310]. Further information is given in the Criticality Safety Status Report [7].

The most significant impact of thermal perturbations in the GDF is that they could lead to the establishment of temperature differentials in the groundwater in the surrounding rocks. Because the density of the groundwater decreases with temperature buoyant flows could be established, with the warmer groundwater in the vicinity of the GDF rising upwards through cooler groundwaters. This is only likely to happen if the host rocks are sufficiently permeable that the increase in buoyancy forces due to heating is sufficient for the Rayleigh number[15] to exceed the critical threshold for convection, and so choice of a low permeability host for heat-producing waste is the key to precluding this possibility. Given that hydrostatic pressure at GDF depth will increase the related boiling point of groundwater, it is highly unlikely that vaporisation of groundwater could occur, even were the temperature to rise significantly higher than planned.

Thermal perturbations could also affect the rate of chemical reactions and could alter some reaction paths in and around the GDF.

6.2 Hydrogeological perturbations (H)

> During the operational phase of the GDF, the open void will provide a significant perturbation to the groundwater pressures and hydraulic gradients in the vicinity of the facility, which will result in a tendency for groundwater to flow into the facility during this period. Once the facility is closed and sealed, the air-filled spaces will begin to resaturate with groundwater.

During the operational phase of the GDF the open void will provide a significant perturbation to the groundwater pressures and hydraulic gradients in the vicinity of the facility, which will result in a tendency for groundwater to flow into the facility during this period. This may result in drawdown of the groundwater table or reduction in groundwater pressures, and may also result in some hydrochemical perturbations as groundwater flows towards the open excavations. Drawdown of possibly dilute surface waters could occur, as could upconing of deeper, more saline groundwater as a result of pumping from the GDF excavations.

The rate of inflow, and hence the extent of hydrogeological and hydrochemical perturbation, will be controlled by the permeability of the rock in which the GDF is constructed.

Once the facility is closed and sealed, the air-filled spaces will begin to re-saturate with groundwater. The time taken for the GDF to re-saturate will depend on the permeability of the host rock (itself affecting the extent of drawdown of groundwater that has occurred to that point in time); the lower the permeability, the longer the resaturation period. In a higher strength rock the resaturation process following closure of the GDF may be complete within a few decades. In contrast, for a lower strength sedimentary rock the timescale for complete resaturation may extend to a hundred thousand years. In evaporites, the absence

[15] In fluid mechanics, the Rayleigh number (Ra) for a fluid is a dimensionless number associated with buoyancy-driven flow, also known as free convection or natural convection. When the Rayleigh number is below a critical value for that fluid, heat transfer is primarily in the form of conduction; when it exceeds the critical value, heat transfer is primarily in the form of convection.

of mobile groundwater means that no inflow will occur during the operational period; any voids in the facility will seal after closure as a result of creep.

Mechanical disturbance and chemical disturbance to the host rock due to the presence of the GDF may also alter the hydrogeological properties, such as the permeability and porosity, of higher strength rocks and lower strength sedimentary rocks. The hydrogeological changes that result from mechanical disturbance are expected to be time-dependent and will evolve as the rock mass around the GDF responds to the perturbed stress field. The greatest effects will occur in the rock close to the facility. Chemical disturbance can perturb hydrogeological properties in a number of ways; the most important is due to mineralogical changes in the rock. The volume of rock affected will depend on the nature of the chemical disturbance and its spatial extent.

On longer timescales the GDF will become part of a regional groundwater flow system that has been modified, to a greater or lesser extent, in respect of the presence of the GDF.

The following subsection provides more detailed analysis of the hydrogeological changes that will occur across the GDF's lifecycle.

6.2.1 Hydrogeological changes associated with GDF implementation

Over the lifetime of the GDF the hydrogeological regime in the surrounding rock will be altered. During construction these effects can be managed, for example through pumping, but this will result in the desaturation of the surrounding host rock. Resaturation times will vary dependent on the geological environment. Over time, the system is likely to recover to hydrogeological conditions similar, but not identical, to those existing pre-construction, although the GDF will always contain volumes of enhanced permeability and could therefore affect groundwater movement at a local scale.

Site characterisation

Investigations undertaken to support site characterisation are expected to include the drilling of boreholes in order to undertake a number of sub-surface tests (such as geophysical and engineering property tests) and to enable the collection of samples for groundwater and rock analysis. Borehole sealing is considered in Section 6.3.8.

Construction and operations (including a period of retrievability)

The design and layout of the GDF, including its orientation, will take site-specific information such as the direction of groundwater movement and tectonic stresses into consideration. The construction of the GDF, and the presence of an operating GDF, will influence groundwater movement in the surrounding geology, causing a drawdown of groundwater and an associated decrease in groundwater pressure in the vicinity of the GDF. While the GDF is operating, the open void, and the ventilation, will provide a significant perturbation to the groundwater pressures and hydraulic gradients in its vicinity and may desaturate the surrounding rock mass. Groundwater at potential GDF depths is expected to be reducing prior to construction; however during operations the oxygenated environment created by the ventilation has the potential to alter the redox potential of the groundwater near to the GDF, creating more oxygenated groundwater conditions. A practical consequence of this may be the oxidation of pyrite (iron sulphide), if present.

The effects of the relatively short period of oxidising conditions in the GDF during the construction and operational period are taken into account when establishing assumptions regarding the initial conditions for the post-closure safety assessment. Furthermore, appropriate consideration needs to be given regarding:

(i) Biofilm growth, which will mainly be associated with the oxidation of dissolved sulphide to native sulphur as groundwater enters the ventilated void

(ii) Evaporation to dryness of even relatively fresh inflowing groundwater, leading to the accumulation of salts on the walls and in skin-zone fractures (the amount of accumulated salts would increase with time, in the absence of any management approach).

Both are discussed in reference [311]; management of accumulated salts may be needed before the commencement of the GDF post-closure period and associated resaturation with groundwater, noting that abrupt, localised salinisation of the ingressing water on contact with accumulated salts could otherwise occur.

As discussed above, groundwater inflow during operations will be managed via dewatering/ pumping and sealing activities. The spatial extent of associated effects will depend on the size of the repository, the host rock composition and the particular conditions encountered, but it is expected that perturbations will be confined to a small region of the host rock around the disposal facility's excavations.

In higher strength rocks and lower strength sedimentary rocks there will be a tendency for groundwater to flow into the facility during this period, both from the overlying and underlying rocks. The rate of inflow, and hence the extent of hydrogeological and hydrochemical perturbation, will be controlled by the hydrogeological properties of the rock in which the GDF is constructed and thus is a highly site-dependent effect.

In evaporites, the absence of mobile groundwater means that minimal inflow will occur during the operational period; self-healing of any EDZ through rock creep will occur.

Post closure

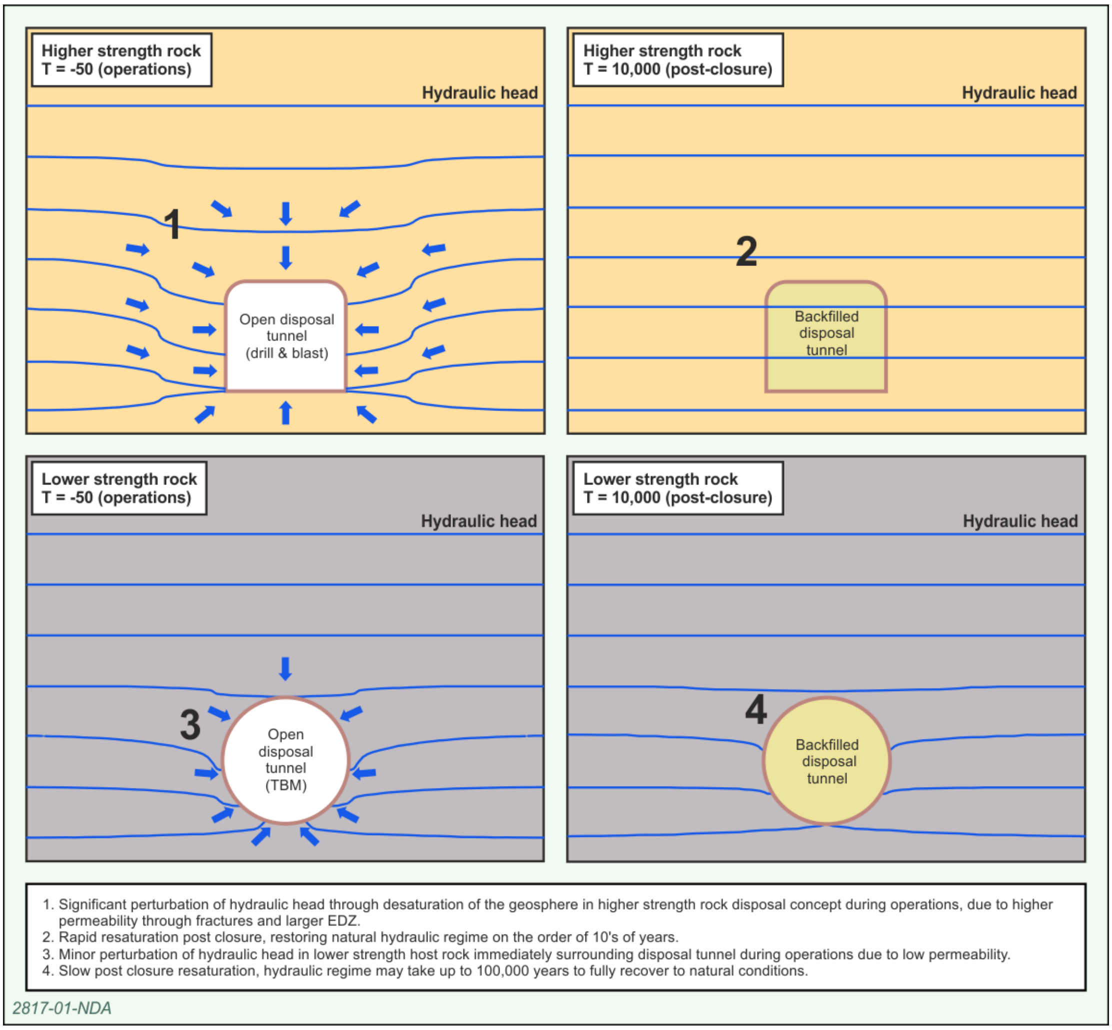
Once the facility is closed and sealed it will re-saturate. The time taken for the GDF to re-saturate will depend on the hydrogeological properties and the engineered barrier system implemented in the host rock.

In a higher strength rock the resaturation process following closure of the GDF may be complete relatively quickly (order of years), although this will be strongly dependent on the degree of fracturing and fracture interconnectivity [312]. In contrast to this, for a lower strength sedimentary rock, the timescale for complete re-saturation and return to pseudo-equilibrium may extend to a hundred thousand years [312]. Figure 31 demonstrates the variability in perturbation of hydraulic head as a result of desaturation caused by the emplacement of the GDF in HSR and LSSR, and subsequent resaturation post closure.

As the system resaturates, reducing conditions are likely to be re-established [313]. The re-establishment of hydrologically-saturated, chemically-reducing conditions will halt host-rock oxidation, slow waste package corrosion, and lower the potential solubilities of some radioelements.

On longer timescales, the GDF will become part of the regional groundwater flow system; it is probable however that its hydrogeological properties will differ from those of the surrounding rocks. The presence of the GDF could affect groundwater movement at a local scale, however as the volume of the facility to surrounding rock mass is small, the presence of the GDF may not alter the larger-scale hydrogeological regime.

Figure 31 Schematic showing the perturbation in hydraulic head during desaturation of the geosphere surrounding the GDF caused by construction and operation and the subsequent difference in recovery rate during post closure resaturation for HSR and LSSR. Magnitude of arrows and extent of drawdown are illustrative only.



The effect of extended operations on the resaturation of the GDF has been modelled for both HSR and LSSR, in each case comparing two simulations representing operational periods of 100 and 300 years [314]. Reference [315] considers some implications associated with the timing of backfilling on GDF evolution.

Reference [314] indicates that, in the case of HSR, the results indicate that the gas saturation and pressure profiles just before closure of the GDF would be virtually identical for the case where the GDF was open and ventilated for 100 years and the case where the GDF was open and ventilated for 300 years. The resaturation will therefore behave similarly, except that it is delayed by 200 years in the case of the extended operational period.

In contrast, in the case of LSSR, the study [314] indicates that a much larger region has been desaturated in the case where the GDF is open and ventilated for 300 years than is the case when it is open and ventilated for 100 years; differences in the gas saturation and pressure fields at the closure of the GDF mean that it will not resaturate in the same manner for the two cases. In addition, it would take longer for the GDF to resaturate in the case where the operational period was extended.

The difference in behaviour noted in [314] in relation to HSR and LSSR is due to the higher degree of fracturing and fracture connectivity in a HSR enabling changes in the system to occur rapidly (on a timescale of one year in the model scenario). In contrast, changes to the gas saturation and pressure profiles in the LSSR occur on a longer timescale (hundreds of years).

6.3 Mechanical perturbations (M)

The principal processes associated with rock deformation are displacements in intact rock, reactivation along existing discontinuities, generation of new fractures and creep.

A number of processes associated with rock deformation are illustrated schematically in Figure 32. The figure, which is based on deformation in a fractured rock, includes the principal deformation mechanisms and shows how they might operate adjacent to, close to and further from underground openings. The four principal mechanisms considered in the figure are:

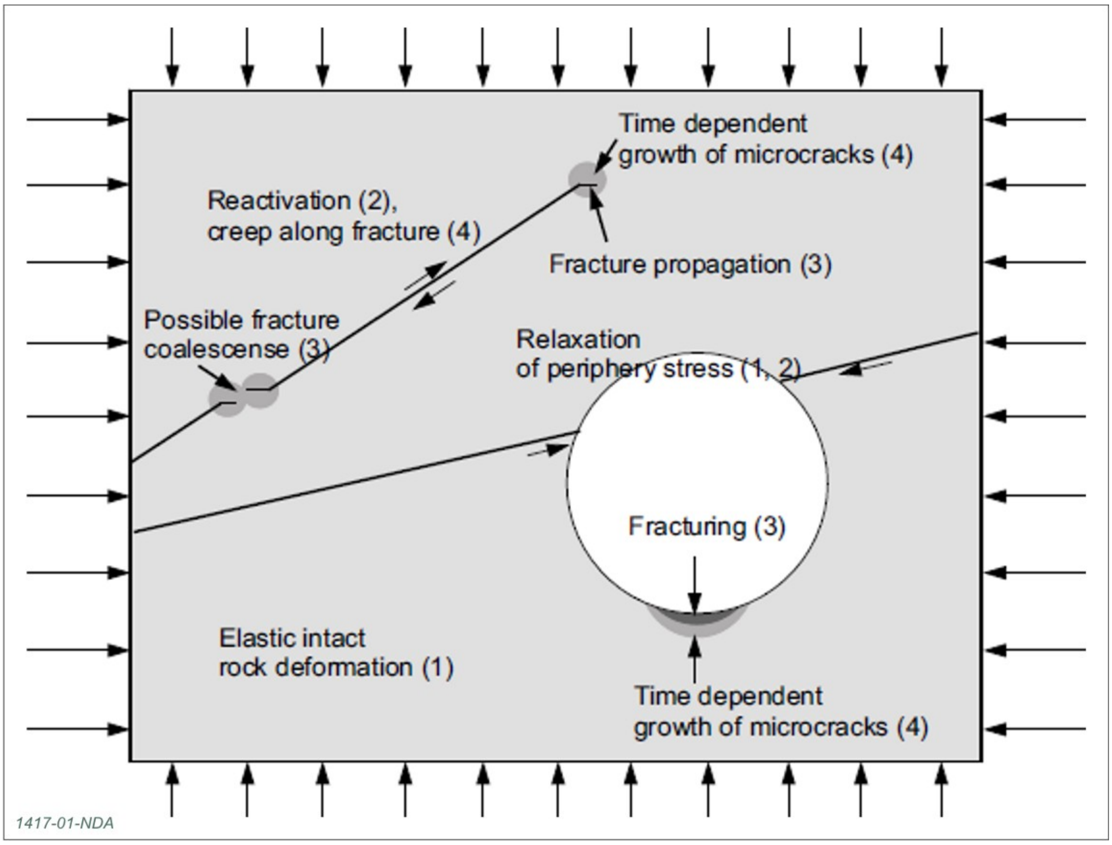
(1) displacements in intact rock. These are elastic, reversible responses that relate applied stress to strain and are governed by two elastic parameters: Young's modulus and Poisson's ratio

(2) reactivation along existing discontinuities. This involves the opening or closing of existing fractures ('normal' displacements) and displacements across existing fracture surfaces ('shear' displacements). Reactivation can occur both in fractures that intersect underground openings and in fractures in the vicinity of such openings

(3) generation of new fractures. This brittle deformation occurs when the applied stress (tensile or compressive) is increased to a point where the rock strength is exceeded. It can occur at the walls of the excavation ('spalling') or deeper into the rock mass, where new fractures can propagate at the tips of existing fractures or can form by the coalescence of existing fractures. Fractures may develop during excavations in LSSR and Evaporite, as well as in HSR. In LSSR and Evaporite, they will however re-seal with time

(4) creep. 'Creep' is plastic deformation that occurs under a constant applied stress. It results in permanent deformation that occurs in a time-dependent manner. In the case of the higher strength fractured rock considered in Figure 32, some creep may occur through the growth of microcracks. Creep occurs in a lower strength sedimentary rock to some degree, so that fractures would not be able to act as flow paths for groundwater movement in the long term. Evaporite rocks are weak and creep easily so that open cracks cannot be sustained.

Figure 32 Processes in a HSR rock volume under load: (1) Displacements in intact rock; (2) Reactivation; (3) Fracturing and (4) Creep displacements.



Aspects of mechanical perturbation as relevant to the GDF are discussed in the following sub-sections.

6.3.1 Excavation Disturbed Zone (EDZ)

The Excavation Disturbed Zone (EDZ) can influence the performance of the engineered barrier system and can also modify groundwater flow around the repository. It is created by the mining/drilling activities during excavation of the GDF.

Excavation of underground disposal vaults, shafts and boreholes for the GDF will perturb the stresses in the surrounding rocks and this, in turn, may induce mechanical changes in the host rocks. This zone of perturbation is called the Excavation Disturbed Zone (EDZ); it can influence the performance of the engineered barrier system and can also modify groundwater flow around the repository. An EDZ is created in the first instance due to the mining/drilling activities during excavation and the redistribution of stresses in the host rock resulting from the creation of void spaces. It may evolve further with time, for example as a result of stress changes during resaturation after closure. Such activities may cause:

- mechanical damage, such as local weakening and/or fracturing of the host rock, which may lead to processes such as rock fall or rock spalling, or creation of an interconnected fracture network and an increase in hydraulic conductivity
- alteration of gas transport pathways
- desaturation and/or changes in local groundwater transport pathways
- changes to the redox conditions within the host rock.

An EDZ occurs in the area immediately surrounding GDF excavations and effects are usually relatively localised. The specific nature and spatial extent of the EDZ are dependent on the characteristics of the geological environment (including the local stress-field), the design of the disposal facility (including GDF depth and orientation) and the excavation method. In order to evaluate any impacts arising from the presence of an EDZ it helps to have an understanding of its geometry, orientation relative to local stress fields, hydraulic properties, solute transport properties and chemical properties, and how these differ from those of the undisturbed host rock [316], as well as how these characteristics are likely to evolve.

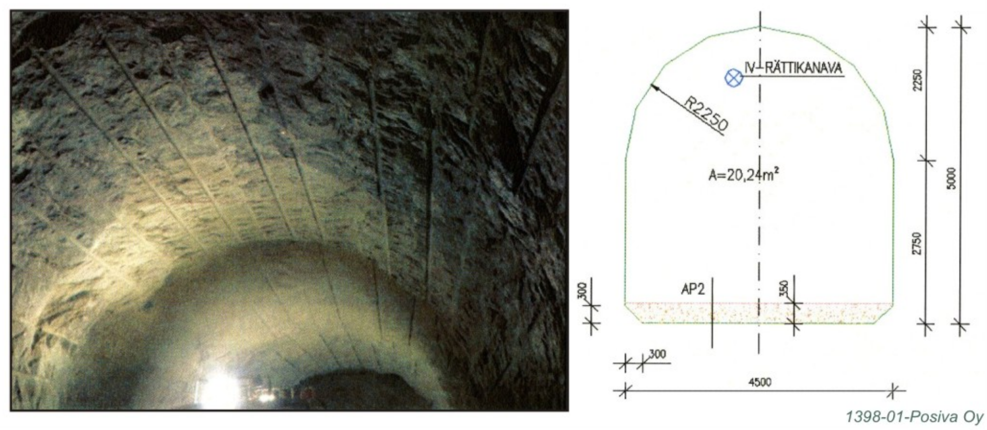
A variety of terms are used to denote the EDZ. For example, it is sometimes referred to as the ‘disturbed rock zone’ (DRZ), particularly in the USA [317]. In some countries the EDZ is subdivided according to the extent of perturbations to the natural conditions. For example, the Belgian radioactive waste management organisation, ONDRAF/NIRAS considers an ‘excavation *damaged* zone’ (EDZ), where changes to some of the host-rock properties are significant enough to potentially affect the performance of the disposal system [318]. ONDRAF/NIRAS distinguishes this from the excavation *disturbed* zone (EdZ), which is more spatially extensive, where changes to the host rock properties occur but have no significant impact on long-term safety or performance [318].

An EDZ will begin to develop as soon as excavation activities commence, due partly to excavation-related vibrations and partly to changes in the stress fields in the rock, which may lead to changes in pore pressure and/or localised fracturing.

The EDZ will have different mechanical and hydraulic properties to those of the surrounding rock. Changes in the stress field can lead to distortion of the local geological environment and consequently changes in rock properties, such as porosity (for a porous medium) or size and geometry of fractures (in a higher strength rock), leading to changes in the groundwater flow [319]. The effect of stress on rocks can vary significantly with temperature and confining pressure. Typically the EDZ will be more extensively fractured, more permeable and have a higher hydraulic conductivity than the unaltered environment. The EDZ may partially desaturate as a result of fracture flow, suction and drainage effects. In addition, changes in the stress fields in the host rock may cause rock spalling and/or the reactivation of pre-existing fractures in some host rocks. Depending on the excavation method used and the nature of the site-specific geology, the EDZ may extend away from the excavated region by a few centimetres to several metres [320, 321]. Box 1 illustrates work carried out at Onkalo, Finland, to investigate the EDZ in a higher strength host rock.

Box 1 Testing rock excavation methods and EDZ formation

Research carried out overseas at underground research laboratories and during site investigations has considered various construction technologies and their impact on EDZ formation. For example, research into GDF excavation methods indicates that the extent of the EDZ will be more limited if tunnel boring machines are used instead of blasting technologies [322, 323, 324, 325]. However, the additional benefits provided by the rectangular cross-section produced by drill and blast, such as ease of waste emplacement and resource usage, and improved cost effectiveness, due to reduced backfill requirements, will need to be considered when choosing the excavation technique. The photograph and illustration below show a research area excavated by drill and blast at Onkalo, Finland for undertaking EDZ research [326].



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6.3.2 EDZ extent

The spatial extent of the EDZ is controlled by the construction method employed and the properties of the host rock. Excavation of the GDF will increase the permeability of the host rock in this region. An EDZ in a higher strength host rock may have the greatest physical extent (depending on construction techniques) and longest duration in time of the three illustrative rock types considered, noting that an EDZ in a LSSR or in an evaporite is likely to be short-lived, due to the propensity of these rock types to re-seal.

The excavation procedure employed to construct the GDF will determine the extent and nature of an EDZ. For example, for higher strength rocks, the use of drill-and-blast may give rise to an initial EDZ of thickness up to 150 cm (with the extent of disturbance reducing away from the drill-and-blast source) and an increase in permeability of up to 3 orders of magnitude (maximising proximal to the excavations), whereas, in comparison, the use of a tunnel boring machine may produce an EDZ of ~1 cm thickness and an increase in permeability of ~1 order of magnitude [327].

Following excavation, subsequent stress redistribution could cause tension, compression and shear in different areas around the drift; the extent of these effects is highly dependent on the nature of the local geology [327].

In higher to moderate strength rocks, including indurated[16] mudrock, fracture reactivation and the generation of new fractures are the principal modes of deformation [328]. Such processes may be instantaneous, although over time they could produce an EDZ which may extend for a distance of up to a tunnel's radius [321, 327]. However, it is only in the

[16] 'Indurated' relates to the hardening of rock by heat or pressure.

region immediately surrounding the excavation that the rock properties are affected to any significant degree. Within crystalline rocks axial permeability may increase by ~ 1 order of magnitude, however the redistribution of stress may only result in an 80% reduction of radial permeability [327].

Sedimentary host rocks, such as clay, respond differently to excavation, dependent on whether they are indurated (hardened) or plastic. Vertical fractures apparent in EDZs within indurated clay environments may result in an increase in permeability of up to six orders of magnitude [327]. Some lower strength host rocks such as plastic mudrocks and clays will also respond by fracturing in the short term [329]. However, although the EDZ may extend for a similar distance, fractures that have a significant impact on the properties of the rock tend to occur within about 1 m of the tunnel walls [327]. In such host rock environments, the long-term hydraulic conductivity of the EDZ may be increased by about one order of magnitude compared with that of the intact rock [407]. Such effects were demonstrated by the Mine-by Experiment project at the Horonobe URL, Japan (hosted in a sedimentary sequence) [330], which confirmed hydraulic perturbations up to 1 m from the tunnel surface and an increase in hydraulic conductivity of one order of magnitude.

Experimental work carried out as part of an European Commission collaborative project examining key processes affecting the long-term barrier performance of near-field systems, NF-PRO, indicated the extent of geomechanical and/or chemical perturbations is very limited in the case of lower strength sedimentary and indurated clay host rocks [331].

The extent of EDZ in evaporite host rocks will be less than that of crystalline environments, and will heal over time by creep, as discussed in Section 6.3.4.

6.3.3 EDZ evolution

Studies have shown that the EDZ impact is limited in lower strength sedimentary host rocks and halite host rock in terms of its effect on groundwater, although it may be more important in relation to GDF-derived gas. Although potentially a more prolonged feature, the EDZ in higher strength rocks will only extend for a short distance into the host rock.

EDZ evolution can be complex. In the short term the rock will respond to excavation, in the longer term it may recover after GDF closure and sealing. As a result, confinement properties of the host rock can be locally altered, including in the vicinity of the disposal galleries and access shafts. This may provide localised areas of higher permeability for water and gas transport; this potential preferential pathway for radionuclides represents one of the key issues which may affect the overall performance of a repository, particularly in scenarios with early container and seal failure [320]. An evaluation of the spatial extent and properties of the EDZ is required in order to assess whether it is of significance to the overall performance of the system.

The evolution and properties of the EDZ have been studied in some detail because of their importance to a range of underground excavations. In the context of radioactive waste disposal, in-situ experiments to investigate the EDZ have been undertaken in underground rock laboratories in a range of geological settings in a number of international projects. Reference [327] provides a summary and comparison of time-dependent processes, parameters and issues for EDZs in different rock types during GDF excavation, operation and closure. Recognising the importance of understanding the EDZ has led to further large scale initiatives such as the NF-PRO [320] and DECOVALEX [332] projects, which have included work to build understanding of EDZ evolution and properties.

The magnitude of the EDZ created in a higher strength rock may be relatively small (depending on factors such as the excavation technique and the orientation of fractures relative to the excavation, as discussed above). Despite this, significant research effort has been spent in developing approaches to characterise and model deformation in fractured rocks and consequent changes to hydrogeological properties. This coupling of mechanical and hydrogeological processes arises because changes in the stress field may alter the apertures of open fractures in the rock, which in turn affects their permeability. In the context of radioactive waste disposal, the characterisation and modelling of an EDZ in higher strength fractured rocks has been recently summarised in [333]. This review described current knowledge about the nature of an EDZ in fractured crystalline rock and then summarised recent coupled modelling projects undertaken as part of DECOVALEX [332]. The review concluded that a range of modelling approaches was suitable for simulating the mechanical and hydraulic evolution of the EDZ.

Once created, recovery of the EDZ in higher strength rocks will be slow, because processes such as rock creep will be minimal. Although it is only in the region immediately surrounding the excavation that the rock properties are affected to any significant degree, its potential to be a long lived feature means that an EDZ in higher strength rocks may have a more significant, prolonged effect than in other geological settings. Mineralisation may also lead to partial sealing of an EDZ in some host rocks, see, for example, Figure 33.

The principal issue for lower strength sedimentary rocks is that GDF-induced disturbances could cause the host rock to fracture and create preferential groundwater flow pathways in what had previously been a very low permeability barrier [334]. The mechanical response of lower strength sedimentary rocks to excavation has therefore been extensively investigated. The convergence of clays around openings is well-known, and is the reason why tunnel linings are required to keep such excavations open. For example, at the depth of the main gallery level (-490 m) in the French URL at the Meuse/Haute-Marne site, plastic deformation is the dominant response to excavation [320]. Although some lower strength sedimentary rocks respond to stress change in the short term by fracturing, there is much evidence from underground excavations for longer-term creep, which causes these fractures to ‘self-seal’ [335]. As with higher strength rocks, the extent of an EDZ around an underground opening in lower strength sedimentary rocks is limited; however, unlike the higher strength rock, the effects are considered to be largely or wholly reversible. The NF-PRO collaborative project combined data on fracture resealing processes, water and gas properties in the damaged zone; data on radionuclide mobility in the chemically altered zone are being integrated to assess the impact of the damaged zone on the overall performance of the near-field system [320].

Preliminary performance assessment calculations have been carried out on indurated clay (Callovo-Oxfordian argillites in France and Opalinus clay in Switzerland) utilising data from the NF-PRO collaborative project on EDZ extent, fracture resealing processes, water and gas properties in the damaged zone, and radionuclide mobility in the chemically altered zone [331]. These have shown that the EDZ impact is in fact very limited and will not affect repository safety in these host rocks.

EDZ evolution within evaporite is expected to behave similarly to that of plastic sedimentary host rocks. With the construction of the WIPP in New Mexico commencing in the early 1980s, there have been approximately 30 years during which time the EDZ has developed in response to initial excavation, enabling real-time analysis of the evolution of an EDZ in rock salt.

A recent summary of the EDZ at WIPP is presented in [336]. Immediately after excavation, the salt responds by micro-fracturing; these micro-fractures develop with time and are most abundant near the opening. On longer timescales, the salt responds in a plastic manner (creep) to close the opening and heals the previously micro-fractured areas. This has been observed through small-scale tests at WIPP, and in salt mines on longer timescales. At the higher temperatures caused by heat-generating waste, the creep capability of the salt increases and, for example, sealing of deposition holes for the heat generating remote handled packages at WIPP by the creeping host rock is expected within about 10 years [337].

Three large-scale field experiments have been performed in the Asse mine in Germany to investigate the coupled THM behaviour of rock salt, and the coupled THM behaviour of crushed salt that could be used as backfill material. The experiments were designed to simulate conditions in the GDF for spent fuel, and were supported by a programme of modelling to build confidence that the system could be adequately understood and predicted.

One of these experiments, the Thermal Simulation of Drift[17] Emplacement (TSDE) experiment, comprised the in-situ measurement of the THM response of the salt formation to the heat release from simulated waste casks under repository-relevant conditions. The experiment confirmed that the salt formation converged on the opening; application of a 3D model showed that the observed behaviour was in good agreement with the model predictions [337]. The lack of mobile groundwater within evaporite deposits means that any temporary increase in salt permeability will not be of significance.

Permeability measurements from the WIPP site were reported in [336] and demonstrate that the permeability of salt samples from WIPP increased by almost ten orders of magnitude as the salt was strained, albeit from a very low initial permeability of less than 10^{-21} m^2 (equivalent to a hydraulic conductivity of 10^{-14} ms^{-1}).

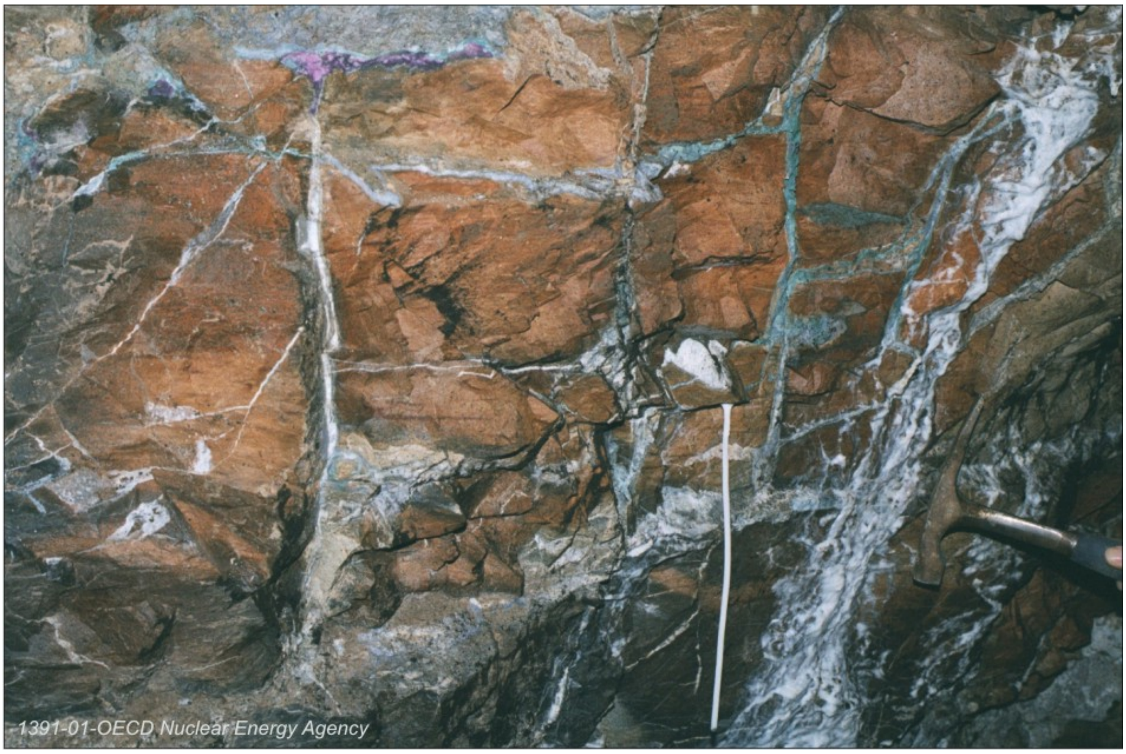
The permeability of salt samples recovered from the EDZ after completion of the TSDE experiments at Asse was of the order of 10^{-22} m^2 (equivalent to 10^{-15} m^2 hydraulic conductivity) [337]. Such permeability values correspond to non-disturbed rock salt and indicated that any EDZ had healed during heating of the rock salt. Therefore, at both ambient and elevated temperatures, the EDZ evolution will reverse and the rock properties will return to their original state within a relatively short timeframe.

In many geological environments, an EDZ will therefore tend to heal and seal over time (either partially or completely) through processes such as rock creep [320]. Mineralisation may also lead to partial sealing of an EDZ in some host rocks. An example of mineralisation observed in natural fractures is shown in Figure 33, from the Maqarin site in Jordan [338, 339]. This site has been studied as a natural analogue in relation to how a cementitious GDF engineered barrier system could evolve and interact with a host rock. Figure 33 shows fractures that have been sealed with calcite as a result of the passage of alkaline fluids at the Maqarin site; this is of particular relevance when considering the evolution of a cementitious ILW disposal concept in HSR and any interaction with the host rock, and could indicate how an EDZ in such a host rock could evolve, including being subjected to mineralisation (Maqarin is further considered in Section 6.4.3, regarding the alkali disturbed zone).

Several methods are available for managing the EDZ during the construction and operational periods of the GDF. It may be possible to use engineered measures such as shotcreting, rock bolts, or the injection of sealants, such as silica sols, to seal the EDZ and/or to prevent it extending further into the intact rock. Seals can also be designed to extend through the EDZ and thereby potentially mitigate the EDZ forming a continuous path for groundwater flow or radionuclide transport. The longer-term evolution of the EDZ and the required management approaches will need consideration on a site-specific basis.

[17] "Drift" here means a passageway in, for example, an underground mine. It may be horizontal or inclined.

Figure 33 Photograph of fractures sealed by calcite due to the passage of high pH fluids through a fractured zone at Maqarin in Jordan [339].



6.3.4 Creep

The plastic properties of lower strength sedimentary and evaporite host rocks means that the EDZ present in these environments is likely to 'self-heal' over time through a process known as creep (highly indurated LSSR may show a reduced propensity in this regard). Rock creep in these host rocks can cause operational issues such as rock fall. However, these can be mitigated by engineering methods. Higher-strength rocks will not self-heal by creep.

In some geological environments (most notably in some lower strength sedimentary rocks such as poorly indurated mud rocks and clays, and in evaporites), the host rock may exhibit significant plastic flow (creep). In such environments rock creep will begin immediately following excavation, driven by the presence of a differential stress due to the creation of void spaces. Scraping of vault walls, ceilings and floors, and/or the provision of strong vault supports may be necessary during construction and operation of the GDF in such rocks to keep disposal areas and access ways open until operations are complete [340].

A study [341] into drift response following excavation in the Callovo-Oxfordian formation at the Meuse/Haute-Marne URL in Bure found that elastoplastic damage mechanisms dominate the behaviour of the drift in the short term, with fracture networks developing due to the semi-brittle behaviour of the rock. They identified that most of the fractures (75 %) appear in shear fracture and 25 % are in extensional fracture. Deformations within plastic environments develop with time, and the creep of the rock matrix and induced fracture propagation are more dominant in the early phase. The extent of fracture networks depends on excavated tunnel orientation versus the in situ stress field. This will be an important consideration during the design of the GDF support system as the engineering methods employed for tunnel support/lining (shotcreting, steel tunnel liners, etc.) were shown by this study to have a significant effect on the evolution of the EDZ [341].

Rock creep has been observed to occur quite rapidly in an evaporite, for example vault walls at Gorleben were observed to creep by up to 60 cm over a 3.5 year period [342]. The US DOE WIPP site in New Mexico creeps at between 75mm and 100mm per year vertically, and between 50mm and 75mm per year horizontally [343].

There is much evidence from underground excavations for longer term creep, which causes these fractures induced by mechanical perturbation to self-heal [329]. These self-healing properties of clays are well studied [344]. Experiments performed on highly cracked samples from the Callovo-Oxfordian argillite and Opalinus clay have demonstrated significant fracture closure and an associated decrease in permeability to very low levels (10^{-19}- 10^{-21} m^2) occurs when the samples are exposed to temperature and pressure, indicating that over time the in situ EDZ is likely to re-seal [344]. Depending on the prevailing conditions (temperature, stress, rheology, etc.) creep is expected to render the permeability of disturbed evaporite rocks similar to that of the undisturbed rock within approximately 200 years [340].

6.3.5 Rock mass instability

The stability of host rocks can be assessed accurately and where necessary detrimental effects, such as rock spalling, can be managed during operations by employing standard engineering practices.

The propagation of fractures in lower strength sedimentary and evaporite environments post excavation may lead to instability of the rock surface, and the potential for rock fall. For example, within eight years of excavation of a test room at the WIPP site a 2m wide unstable zone in the roof formed, causing it to collapse [343]. Such environments will therefore be carefully managed and supported during the operational phase through standard engineering practices such as rock bolting, shotcreting, and the application of liners (made from, for example, steel or concrete).

In the geosphere, especially in regions where high levels of stress exist, pieces of rock can be broken off the intact rock body in a process known as spalling. Such spalling could potentially occur around underground vaults and is a common mechanism of rock weathering at the surface of a rock when there are large shear stresses behind its surface. This form of mechanical weathering could be caused by temperature fluctuations, mechanical unloading, or salt deposition, and is a mechanical perturbation that will be introduced during the excavation of tunnels and deposition holes.

SKB conducted the Äspö Pillar Stability Experiment, with the objective of determining the spalling/yielding strength of a granitic rock mass. This experiment was modelled as part of DECOVALEX Task B [345], two vertical boreholes of 1.75 m diameter and approximately 6 meters deep were excavated at 450 m underground, and were separated by a 1 metre thick pillar of Äspö diorite containing fractures. Back calculation of the spalling strength of this rock was found to be comparable with other granitic rock masses, and demonstrated that it was possible for modelling techniques to predict the response of rock masses to thermal and mechanical stress at the GDF scale.

6.3.6 Void space

Void space, which relates to large scale empty regions (also referred to as macroscopic voids) within or around packages in the Engineered Barrier System (EBS) of the GDF, will be present during operations and post closure.

The presence of void space in a waste package reduces confidence in the predictability of wasteform and waste package performance, and may undermine steps taken to engineer particular properties or performance criteria for the GDF. Underground void space is inherently unstable, due to the lithostatic load, and solid material will tend to migrate under the applied load to fill voids. It is recognised that the likelihood and extent of any post-closure mechanical disruption to the GDF will be influenced by site-specific host rock properties.

Depending on material properties, migration of solid material can be caused by fracturing and collapse, or by plastic deformation (creep). Were such migration to happen, void space in individual stacked waste packages could coalesce, leading to disruption in the desired performance of the EBS. The greater the potential for formation of collapse structures, the greater the uncertainty regarding backfill performance.

If the coalesced void space were large enough, mechanical evolution of the host rock, involving rock fracturing and block movement, could occur. Although this is likely to be a localised effect limited to the immediate vicinity of the GDF opening, it could introduce void space into the geosphere immediately adjacent to the GDF, thus effectively increasing the size and nature of any excavation damage zone. Barrier properties of the host rock could be bypassed, in whole or in part, which could lead to an increased rate of migration of radionuclides from the GDF.

Ongoing RWM work (see [11] Task 866 and [346] for further information) is considering a series of scenarios in an effort to bound the consideration of void space at the current generic stage. This work was commissioned to inform the development of guidance to waste packagers (as part of the RWM Disposability Assessment process) on the tolerability of in-package void space, and is considering the potential issues that could be caused by the presence of void space in the GDF in the post-closure period.

This ongoing work has identified where and how the presence of open void space within waste packages may be beneficial (and conversely, detrimental) to safety performance, and for which host rocks and disposal concepts the effects may be most significant. It sets out the options for managing void space in waste packages, in particular describing:

- the potential constraints that may be introduced by accepting open void space within waste packages
- the safety arguments that can be made in support of accepting open void space in waste packages
- where it may be appropriate to limit open void space in waste packages, and potential limits
- where the presence of open void space in waste packages may be beneficial and how this may be factored into the potential limits
- the practicalities and implications of options for filling voids in packages immediately prior to despatch for disposal in the GDF.

On the basis of the ongoing study, RWM proposes to develop further guidance to waste packagers on managing the post-closure implications of void space through its Disposability Assessment process.

6.3.7 Gas pressurisation

Due to the presence of fractures, gas pressurisation is unlikely to occur within higher strength host rocks. However, the low permeability of lower strength and evaporite host rocks may lead to gas being constrained and subsequent pressurisation that could perturb the geosphere locally.

After closure of the facility and re-saturation by groundwater, gas will be generated by corrosion, degradation of organic material and radiolysis. This could lead to an increase in pressure. Certain geological environments and GDF concepts will allow the gas to migrate into the geosphere with little impact on the rock. However, in other environments the gas could be constrained, potentially leading to an increase in pressure. This increase could then be relieved by the opening of existing fractures or the creation of new ones. This could have implications for the flow of groundwater, or the release of gaseous radionuclides [6], and thus could accelerate radionuclide transport rates. Once any overpressure that may be created has dissipated, through escape of the gas, these pathways may close or re-seal.

In higher strength rocks, gas is able to migrate through the fractures without generating overpressure in the rock. No significant mechanical perturbation would occur.

In lower strength sedimentary rocks and evaporites, gas migration could be constrained, leading to an increase in pressure in the vicinity of the GDF. This increase could be relieved by the opening of fractures, either existing or newly created. This mechanical perturbation could change the stress field and have implications for the flow of groundwater. Gas migration is considered further in the Gas Status Report [6].

6.3.8 Borehole sealing

Technologies exist, developed both for geological disposal and within other industries, which allow boreholes to be sealed effectively so that groundwaters cannot migrate through them. The specific approach to borehole sealing will be determined on a site-specific basis, dependent on rock properties.

The drilling of boreholes, some extending to over one thousand meters depth, will be an integral part of the site characterisation process and is vital to building an understanding of the geosphere and developing a fully integrated Site Descriptive Model (SDM). However, these investigative boreholes must not compromise the containment properties of the facility. An unsealed borehole has the potential to act as a conduit for groundwater or gas migration and could act as a pathway for the migration of radionuclides away from the EBS. Depending on the hydraulic properties of the site, an unsealed borehole may provide a route for groundwater to the surface or an increased rate of groundwater recharge [347]. Borehole sealing aims to reduce the hydraulic conductivity of the borehole to a level equal to, or below that of, the surrounding host rock. This will ensure that boreholes are not a preferential pathway for water or gas, and any movement of radionuclides that does occur will be through natural permeability in the host rock.

It is generally the case that more than one component is used to seal boreholes after use [348]:

- one (or more) components will act as a low-permeability barrier in order to restrict the flow of gas or water through the borehole and therefore prevent the transport of radionuclides. This component (a 'seal') is generally made of natural clay materials, such as bentonite. Bentonite seals are used in sections of the rock where permeability is low and the host rock is not fractured. The clay material is emplaced into the borehole and swells on contact with water for a tight, impermeable seal against the host rock. In the SKB/Posiva design concept [349, 350], the bentonite clay is emplaced as heavily compacted discs within a perforated copper container which allows rapid emplacement without swelling occurring before the seal has reached its intended depth [351]. Other design concepts involve emplacement in the form of pellets, or as a grout or slurry [348]. The exact composition of the bentonite is chosen for its long term stability and its ability to remain operational at long times post-closure.

- concrete ‘supports’ or ‘plugs’ are also used across most borehole sealing design concepts [348]. In HSRs these are emplaced into sections that are heavily fractured and exhibit high permeability. Groundwater movement in these transmissive features could erode the less coherent clay seals, possibly causing degradation of their performance and enabling transport of radionuclides over time. In Nagra’s LSSR design reference, concrete supports are emplaced in ‘intermediate zones,’ to support the clay seals [352]. It is not the function of the concrete to provide an impermeable barrier, but to provide the mechanical strength to support the surrounding host rock and overlying clay seals and to avoid erosion from significant groundwater movement. It is important that the composition of the concrete does not lead to the production of high pH leachates during interaction with groundwater, as this may lead to degradation of the surrounding clay, affecting its ability to swell and form a tight seal. A concrete formulation containing silica fume, quartz sand and a small quantity of cement is used to avoid high pH leachates forming. The cement binder is not required to remain stable for long periods and will eventually be lost by leaching in groundwater; it is however required to provide sufficient mechanical strength shortly after emplacement. In the longer term, the remaining quartz sand will provide the long-term mechanical support for the overlying seals [348].

RWM has an on-going project on borehole sealing (see [11] for further information). Output to date from this project has been published in references [348, 353 and 354].

6.4 Chemical perturbations (C)

The extent and nature of chemical alteration driven by GDF derived materials (such as the formation of an alkaline disturbed zone and a source of organic materials) will be site dependent. Secondary mineral precipitation has the potential to seal fractures and reduce groundwater flow from the facility.

Excavation and subsequent backfilling of underground openings in the GDF (including disposal vaults and tunnels, access and service tunnels, and other underground working areas) will perturb the geochemical conditions in the deep subsurface. These perturbations, which constitute a chemically disturbed zone (CDZ) in the host rock surrounding the GDF, can be divided into those that occur during GDF construction and operational periods, largely as a result of the excavations in the host rock, and those that occur over a longer timeframe due to the presence of the engineering materials introduced into the host rock. This section introduces each of the major sources of chemical perturbation constituting a CDZ: the oxidised disturbed zone (ODZ) and the alkaline disturbed zone (ADZ). The processes driving each of these perturbations are discussed, followed by the potential timescales over which these perturbations are likely to occur. Evidence from analogue, experimental, and modelling studies is presented.

6.4.1 Sources of chemical perturbation

Materials present in the engineered barrier system of a disposal facility, including buffer/backfill, container, waste grout and the waste itself will provide a source of chemical perturbation to the geosphere when mobilised in groundwater. The exposure of the host rock to air following excavation will also drive chemical changes in that host rock, via oxidation.

When considering the possible development of a chemically disturbed zone, the presence of large amounts of cement-based backfill and grout in the EBS in ILW / LLW vaults of the GDF is usually identified as the most significant likely contributor. However, other factors may also be important in specific geological settings.

The excavation of underground openings at a depth where the rocks are normally saturated with groundwater will necessarily introduce air into contact with the freshly excavated host rock. Furthermore, a safe working environment for construction activities within the excavations requires ventilation and drainage that may act to enhance the changes to the surrounding host rock by maintaining a supply of fresh air and encouraging the drying out of the host rock adjacent to the excavation. The chemical changes to the host rock that may arise from these interactions are discussed in the following subsection.

The effect and implications of evaporation to dryness of even relatively fresh inflowing groundwater, leading to the accumulation of salts on the walls and in skin-zone fractures needs consideration. Management of accumulated salts may be needed before the commencement of the GDF‘s post-closure period and associated resaturation with groundwater, noting that abrupt, localised salinisation of the water could otherwise occur [311].

A further source of potential chemical perturbations in the host rock is due to microbial activity during the period of construction and operations. The combination of a warm, humid environment, possibly with permanent lighting, and a rich variety of nutrient and energy sources is likely to give rise to microbial activity in the form of, for example, algal growths and biofilms associated with damp patches on tunnel walls or in drainage channels (see also the Behaviour of Radionuclides and Non-radiological Species in the Groundwater status report [5]).

Studies on microbial activity in the near field have tended to focus on the potential impact of processes such as oxygen uptake [355], sulphate reduction [356] or metal corrosion [357] in the post-closure period. However, microbial activity during the open period could give rise to chemistry that influences the organic content of groundwater in the surrounding host rock after backfilling of the GDF. The key points are whether the source could be significant, especially in host rocks that already contain organic material, as might be particularly the case for some lower strength sedimentary host rocks, and whether it persists for long enough to have any influence on radionuclide transport in the geosphere. Even for disposal concepts for which an extended open period (up to 300 years) is considered, microbial activity is expected to be far more significant for the integrity of the EBS structures than the geosphere [358]. Thus, organic materials that form as a result of microbial activity are not considered further here. Recent work has investigated the potential for the metabolism of microorganisms to be utilised in such a way so as to seal fractures within rock [359]. This is an emerging science, and we will observe developments in this field as they continue into the future.

6.4.2 Oxidised disturbed zone

The construction of the GDF will expose fresh surfaces of the host rock to air, leading to oxidation of the rock. The extent of oxidation into the host rock will be related to the rock properties and duration of operations. Following closure, the GDF environment will quickly recover to anoxic conditions. Therefore, the long-term impact of an oxidised disturbed zone on the host rock is expected to be insignificant.

The region of host rock around underground excavations (the excavation disturbed zone, EDZ) will become partially desaturated due to the loss of porewater to the adjacent air-filled opening. Oxygen present in air will be able to diffuse further into the host rock, creating a zone in which the expected reducing conditions in the groundwater are perturbed by the presence of oxygen.

The oxygen may react with the host rock, giving rise to changes in both the host-rock mineralogy and the composition of the porewater.

Carbon dioxide in air may also react with the porewater. However, CO_2 content of the air (approximately 400 ppm by volume) and the likelihood that the porewater already contains dissolved carbonate (typically as bicarbonate, HCO_3^-) means that the extent of any chemical perturbation solely attributable to carbon dioxide present in air will be minimal in comparison to the extent of any chemical perturbation resulting from oxygen present in air (on a theoretical assumption of the absence of any cementitious material in the GDF; see section 6.4.3 for a consideration of an alkali disturbed zone).

The nature of the host rock and the EDZ around the excavations, and the presence of any tunnel or vault liner (such as shotcrete or structural concrete), will determine the distribution and extent of the perturbations due to atmospheric oxygen.

Processes

The development of an oxidised disturbed zone arises from a number of processes:

- oxygen diffusion into the host rock
- inorganic reactions between the oxygen and susceptible minerals in the host rock
- microbial activity
- alteration of the porewater composition due to oxidation reactions
- precipitation of secondary minerals.

The interaction that is of greatest concern is the oxidation of sulphide minerals that may be present in host rocks. This is the process that gives rise to acid mine drainage and has also been implicated in damage or even failure of tunnel walls and liners [360]. Oxidation of the commonly occurring mineral pyrite (FeS_2) results in the formation of sulphuric acid due to the reaction:

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O \rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4H^+$$

As noted by West et al. [358], this reaction is often found to be autocatalytic but, under relevant GDF conditions, the inorganic effects may be masked by the effect of microbes (particularly sulphate reducing bacteria) that can thrive in local acidic conditions.

Pyrite oxidation is often associated with the precipitation of iron hydroxides and gypsum ($CaSO_4.2H_2O$), thus this reaction can change the mineralogy of the host rock near exposed surfaces, as well as the porewater, both of which may subsequently have an influence on radionuclide migration. Note that gypsum may not be commonly formed, because it only becomes insoluble where dissolved sulphate exceeds about 2,500 mg/L; formation of a range of ferrous and ferric hydroxysulfate minerals (for example, melanterite, jarosite, copiaite, coquimbite, etc.) may be more likely. This is important because, during resaturation, dissolution of gypsum does not affect fluid pH, but the hydroxysulfates are strongly acid-generating when they finally dissolve [361].

The impact of an oxidised disturbed zone in fractured crystalline rocks is expected to be localised and short-term. Posiva [362] states, "*The disturbances induced by redox processes during the excavation and operational phase are expected to have only a limited effect on the geochemistry of the near field after EBS emplacement*." Furthermore, there is no expectation that there will be any effects extending into the geosphere beyond the EDZ.

The NEA FEP catalogue for argillaceous media [363] notes that, "O*bservations in the Boom and Opalinus Clays suggest that while oxidation effects may be evident, they are spatially restricted and modify neither the geochemical (redox) state nor the physical properties of the formations.*"

This is in agreement with the approach of Nagra [364], which notes that oxygen migration into the EDZ around the tunnels for spent fuel (which are expected to be open for only about 2 years) will oxidise less than 1% of the pyrite and will have no significant long-term impacts.

Timeframe

The penetration of air and oxygen into the host rock around underground excavations occurs only during the open period. The open period will vary for different underground structures in the GDF: tunnels for HHGW disposal may be open for 2-5 years, whereas access tunnels and shafts linking to the surface may be open for over 150 years, taking account of the period of underground investigations, construction of the disposal areas, disposal operations (including new build spent fuel) and closure. It is worth noting also that in many rock types, underground openings that are required to remain open for extended periods of time, such as access and service tunnels, are likely to have substantial linings to prevent rock fall and to inhibit groundwater ingress. Such linings will also act as a barrier to groundwater evaporation in the tunnels and to the diffusion of air from the tunnels into the host rock.

After backfilling of ILW/LLW vaults, the volume of air remaining in the excavations will be limited to the porosity of the buffer or backfill material and void space in the waste packages. Any oxygen present is expected to be used quickly by the corrosion of metals, particularly steel, oxidation of buffer and backfill components (such as pyrite) and microbial activity. In the disposal vaults for ILW/LLW, the use of a cementitious backfill means that the amount of oxygen remaining will be limited as much of the initial porosity is filled by cement mixing water at the time of emplacement.

The rate of oxygen uptake determined for the various processes does not necessarily represent how long oxygen will persist in the GDF, as this is dependent on a larger number of factors, such as the amount of oxygen, the presence of viable microbes and available nutrients, the availability of reactive minerals, the rate of saturation of the EBS and so on. However, the rates do support the assertion that oxygen depletion in the near field could be complete on a timescale of a few years to decades [364]. Pedersen [365] suggests that all oxygen will be consumed in less than a year in sealed tunnels in crystalline rock after repository closure. The apparent lack of significant microbial activity in highly compacted, dry bentonite [365, 366] suggests that there is more uncertainty regarding whether oxygen uptake will occur as rapidly in host rocks in which resaturation is slow, for example Opalinus Clay. However, in both fractured crystalline and sedimentary (clay) host rocks, the contribution of the oxygen remaining in the EBS to the oxidized disturbed zone around the GDF is expected to be minor compared to the oxygen available during the open period. This is because reactions to remove trapped oxygen will take place within the EBS, or at the interface between the EBS and the host rock, thus preventing substantial diffusion into the host rock.

6.4.3 Alkaline disturbed zone

The use of high volumes of cementitious materials in ILW/LLW disposal concepts will give rise to an alkaline plume. This may seal fractures in the surrounding rock through the precipitation of secondary calcite mineral phases.

The source of an alkaline disturbed zone (ADZ) is the leachate produced by the interaction between cementitious materials used in the GDF and groundwater. Cementitious materials may constitute a significant part of the EBS. For example, cementitious backfill, such as Nirex Reference Vault Backfill (NRVB), used in vaults for low and intermediate-level waste may be utilised so as to provide a high pH environment within the engineered barrier system, but groundwater movement and diffusion can extend the alkaline effects into the far field. Much ILW/LLW is also conditioned or encapsulated in cement-based grouts, although these grouts are less porous and exhibit somewhat lower pH than NRVB; thus vaults for these wastes represent a significant potential source of chemical perturbation for the geosphere.

Concepts for HHGW disposal that make use of bentonite in the EBS usually avoid the use of high pH cement-based materials as far as possible, because of the potential for detrimental interactions between cement and bentonite. However, there are many uses for cementitious materials that are difficult to avoid in underground construction and operations, for example, structural concrete is needed in many host rocks to ensure a safe working environment, with tunnel linings and floors required to prevent rock fall or host rock convergence. Even if the disposal drifts or galleries that are open for a relatively short time can be constructed without concrete, it may still be required for access tunnels and other underground areas which are open for much longer periods. Cement-based injection grouts are also commonly used in fractured host rocks to stabilise rock during excavation and thereby reduce water inflow. Given that interaction of these materials over time with groundwater could potentially give rise to a plume of high pH porewater that would detrimentally affect the properties of the bentonite present in the engineered barrier system, much work has been undertaken to consider alternative materials such as lower pH cementitious grouts (for example, [367, 368]).

Processes

The disequilibrium between the host rock - natural groundwater system and the high pH porewater from an ILW/LLW vault engineered barrier system has the potential to drive changes in the geosphere that significantly affect its properties with respect to radionuclide migration. The interaction between high pH porewater and the surrounding geosphere will involve a range of processes:

- mixing of the high pH porewater with groundwater
- alteration of the host-rock mineralogy
- secondary mineral precipitation
- changes to radionuclide retardation in the host rock
- changes to host-rock porosity
- changes to host-rock permeability.

The effect of each of these processes is briefly described below:

- mixing of the high pH porewater with bicarbonate-bearing groundwater is likely to result in the precipitation of carbonate minerals, specifically calcite that will tend to reduce porosity at the mixing interface
- alteration of the host-rock mineralogy; this depends on the minerals present, but swelling clays have been shown to be particularly vulnerable to dissolution by

young cement porewater; the evolved cement porewater has less effect. Carbonate minerals other than calcite are also vulnerable to dissolution, but may be replaced by calcite

- secondary mineral precipitation will tend to result in phases similar to CSH phases (including magnesium variants in some rock types), hydroxides and some silicates, possibly including zeolites
- changes to radionuclide retardation in the host rock may result: from changes in the phases along flow paths due to precipitation of secondary minerals, some of which may have different retention properties from the primary minerals; from changes to the access to rock matrix adjacent to fractures or to pore geometry within the host rock; or from changes to the surfaces of the minerals that reduce the potential for ion-exchange reactions
- host-rock porosity is likely to reduce due to secondary mineral precipitation, at least in the proximal part of the plume
- changes to host-rock permeability will depend on the relative amounts and locations of dissolution and precipitation and how they modify the flow-path characteristics, but the tendency may be for reduction of permeability in some areas to cause changes to the local flow conditions and hydrogeology.

It is expected that the extent and significance of these processes will need to be assessed on a site-specific basis.

The cementitious materials of concern are, at their simplest, a mixture of a cement binder, such as Ordinary Portland Cement (OPC), and water. The dry cement clinker contains a large proportion of lime (calcium oxide) along with silica, some alumina and calcium sulphate, in phases that react exothermically with mixing water to produce hydrated phases, usually termed CSH phases[18]. These phases are non-crystalline (sometimes referred to as gel phases) that are thermodynamically metastable with respect to more crystalline forms, but kinetically persistent at the relatively low temperatures expected in and around an ILW/LLW vault. It is the formation of these cement phases that causes the familiar hardening of cement paste over a few hours.

Other commonly used materials in concrete and mortar include:

- aggregate (such as sand and gravel) is a filler that is largely unaffected by the cement reactions but, for example, can provide the compressive strength for structural concrete
- pozzolanic materials such as pulverised fly ash (PFA) or blast furnace slag (BFS) that react with the OPC binder during the hydration reactions. As they contain a lower proportion of CaO than OPC, they can act to reduce the amount of portlandite in the hydrated cement and also reduce the heat emitted during hydration reactions, which helps to avoid thermal effects such as cracking in solidified wasteforms.

Research considering the interaction between low pH injection grout (pH c. 10) and groundwater in order to assess the potential for formation of an ADZ around the grout emplacement has concluded that the potential for the formation of alkaline leachates was extremely restricted with these grouts [362, 369, 370, 371]. Furthermore, precipitation of calcite due to mixing with groundwater in the longer term will buffer the leachate pH close to groundwater values. In combination with the limited potential to form hyperalkaline

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[18] In cement terminology, calcium oxide (CaO) is reduced to C, silica (SiO_2) becomes S, alumina (Al_2O_3) A, and H_2O is H, so that CSH phases are hydrated calcium silicates and CAH phases are hydrated calcium aluminates. Other cement phases contain sulphate ($\underline{s}$), for example ettringite (CASH).

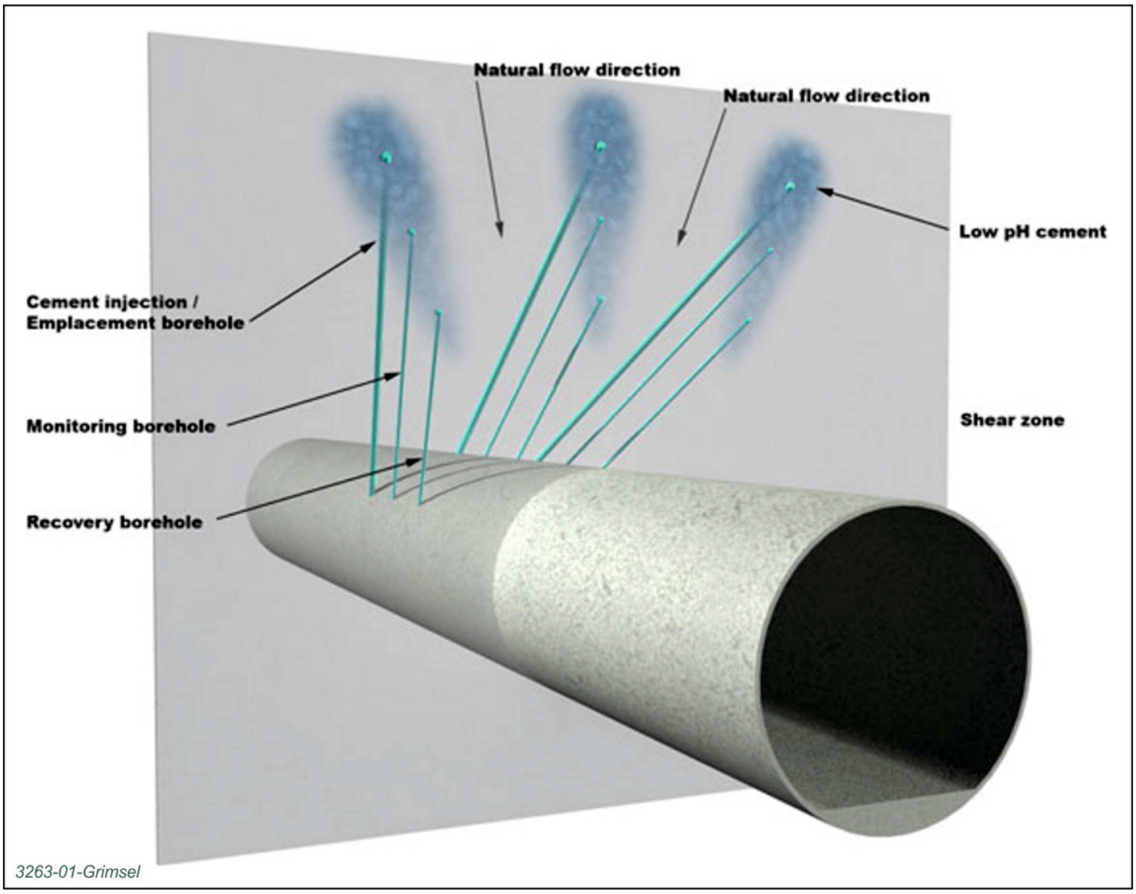
leachates, these processes are expected to ensure that the presence of small amounts of low pH grouts and shotcretes in the repository at disposal depth have no significant effect on the geosphere properties in the long term.

A review of the current understanding of the detailed processes involved in cement degradation in groundwater is given in [372, appendix F3], and Soler [373] has summarised the development of chemical models of the dissolution of CSH phases in cement.

The implications of the development of an ADZ are likely to include a reduction of groundwater flow over time through an ILW/LLW vault employing a cement-based barrier. Two-dimensional reactive-transport modelling by Pfingsten [374] for a cement body surrounded by groundwater on all sides showed that precipitation reactions, which block porosity at the interface between the cement and the host rock, occurred on all surfaces due to the diffusion of solutes where there was no advective transport. Applied to an ILW/LLW vault employing a cement-based barrier, this suggests that armouring of the reaction zone between the cement and groundwater could, at best, maintain diffusion-dominated conditions within the engineered barrier system and may significantly reduce the extent of any ADZ. However, in a fractured higher strength rock, the question is whether minor earth movements could reactivate fractures and break through the armoured reaction zone, allowing groundwater fresh access to the backfill. Such a mechanism has been used to explain the observed periodic reactivation of fractures completely closed by reaction products of the hyperalkaline groundwater system at Maqarin, Jordan [375] (Figure 33).

To enhance our understanding in relation to the ADZ, we are currently participating in the Long-term Cement Studies (LCS) project at the Grimsel Test Site, Switzerland (see [11], Tasks 381 and 401). The LCS project is combining field-scale and laboratory experiments with thermodynamic modelling studies to develop understanding of high-pH cement interaction effects in the engineered barrier system and the geosphere in order to make confident, robust and safety-relevant predictions of future system behaviour, irrespective of the host rock, engineered barrier system and waste type (Figure 34) [376]. A key aspect of the LCS project involves cement sources emplaced in the advective flow system at the Grimsel Test Site. The development and movement of the high-pH plumes is currently being monitored under near-natural and therefore GDF-relevant flow conditions. The LCS project is ongoing, starting in 2006; recent RWM-funded output includes [338, 377, 378, 379].

Figure 34 Long Term Cement Studies (LCS) Concept (figure taken from [376], copyright © 2015 Grimsel Test Site, Switzerland)



6.5 Geomicrobiology

> Microbes will be introduced to the GDF in the wastes and materials used to construct certain engineered barriers and during operations. Microbial activity in the geosphere is generally located on chemical or physical interfaces, usually within biofilms.

Microbes will be introduced to the GDF in the wastes and materials used to construct certain engineered barriers and during operations. For example, natural bentonite clays often contain microbes. Microbes are also present naturally at depth in many rocks.

Microbial activity in the geosphere, as in any environment, is generally located on chemical or physical interfaces, usually within biofilms. Their impacts can be both physical (for example, altering porosity) and/or chemical (such as changing sorption behaviour). Recent work by Meleshyn [380] undertook to qualitatively evaluate the relevance of microbial activity for the long-term performance of a clay-based GDF for HHGW, and to identify which safety-relevant processes and properties can be potentially influenced by this activity. Reference [380] concluded that deterioration of clay properties accompanying destabilization and destruction of clay mineral structure as a result of microbial action can be considered as the primary microbial impact on clay. The study [380] identified eight clay properties essential for maintaining the ability of the disposal system to contain radionuclides and retard their migration: swelling pressure, specific surface area, cation-exchange capacity, anion-sorption capacity, porosity, permeability, fluid pressure and plasticity. These properties can potentially be influenced by microbial processes in clay-based materials and claystone within a repository. Radioactive waste containers and over-packs made from cast metal or steel represent a further component of the engineered barrier system which can be strongly affected by microbial activity in the clay buffer or in the adjacent host rock.

Work reported in [381] broadly summarises the interactions between microorganisms and the different components of geological disposal facilities (wastes, engineered barriers and natural barriers) and highlights how these interactions influence the behaviour of these components. The tools and techniques available to investigate the microbiology of a geological repository and its associated geology have also been reviewed from the perspective of how such data can be integrated into safety case approaches. The review in [381] presents the following conclusions:

- **Microbiology of relevant geological formations**
  - It is recognised that microbes live in a wide range of geological environments. The reviewed work indicates that all the identified general geological environments in the UK will have an indigenous microbial ecosystem which will be influenced by environmental conditions such as the availability of nutrients and energy for microbial use, groundwater flow, the geological history and characteristics of the site, including recent usage, and the site-specific geology.
  - It is recognised that microbiology can influence a wide range of safety-relevant processes. Consequently, microbiological investigations are typically included in site-investigation studies. The information obtained will assist in understanding and predicting the performance of the GDF into the long-term future.
- **Microbiology of the geosphere**
  - Microbes can impact on solute transport processes and thus influence radionuclide migration in the geosphere. This is an area of active research. Microbial transformation of organic complexing agents has the potential to reduce radionuclide migration in the geosphere. Additionally, gases such as hydrogen and methane generated within a repository may be subject to further microbial transformations as they move through the geosphere.

Reference [381] indicates that is not possible to ascertain which microbial effect or effects will predominate in the EBS and/or the geosphere; microbial effects will be dependent on each specific GDF site, the type of waste and the GDF concept.

We recently published a microbiology research strategy review [382]. We are also participating in the recently-started European Commission "*Influence of microbial processes on geological disposal of radioactive waste*" (MIND) project [383]. This project brings together fifteen European groups working on the impact of microbial processes on safety cases for geological repositories across the EU, focusing on key questions posed by waste management organisations. The emphasis is on quantifying specific measureable impacts of microbial activity on safety cases under repository-relevant conditions, thus altering the current view of microbes in repositories and leading to significant refinements of safety case models currently being implemented in order to evaluate the long-term evolution of radioactive waste repositories.

6.6 Coupled processes

> Many of the processes potentially affecting the GDF, for both the natural evolution of the geosphere and those induced by the GDF, are coupled (that is, each process potentially affects the initiation and progress of all other processes). Such process coupling could be linear or non-linear.

An important consideration in radioactive waste management studies is that many of the processes potentially affecting the GDF, for both the natural evolution of the geosphere and those changes induced by the GDF, are coupled. For example, chemical changes such as the mineralogical changes caused by cement/rock interaction may seal fractures or pores in the surrounding rock and so influence groundwater movement in the region of the facility. As a consequence, developing an understanding of the expected couplings and a capability to model those effects is central to our geosphere research. Coupled processes are discussed here in broad terms in the context of the interactions between two or more processes, whether or not there is a feedback loop. Such process coupling could be linear or non-linear.

Coupled processes have been acknowledged by RWM and the wider international radioactive waste management community as being of potential major significance in the assessment of post-closure safety for geological disposal facilities (GDFs) for radioactive waste. To progress our understanding in this area, our ongoing coupled processes research (see Tasks 381 to 415 in our S&T Plan, [11]) supports our capability to model coupled process sets and our understanding of their potential significance to post-closure safety, site investigations and the design of the GDF. A key aspect of this project involves active participation in the international collaborative DECOVALEX project [332], which is developing and testing models of coupled THMC processes.

Sections 5.1 to 5.4 have introduced individual THMC processes typically considered in relation to the GDF for radioactive waste. Process couplings have been classified by the main drivers in terms of thermal (T), hydrogeological (H), mechanical (M) and chemical (C) processes, collectively "THMC coupled processes". Gas (G) can also be considered in relation to coupled processes, collectively "THMCG processes". Issues relating to gas are however considered in the Gas status report, see [6]. Recent work by RWM [384, 385] has indicated that inventory-derived non-aqueous phase liquids (NAPLs) are unlikely to enter the geosphere; NAPLs are therefore not considered in this report, although they are discussed further in the Behaviour of Radionuclides and Non-radiological Species in Groundwater Status Report [5].

The specific couplings of significance depend on the details of the concept, design and host geology and cannot be investigated in detail until site- and concept-specific information is available. However, in RWM's current preparatory studies phase our understanding of the expected couplings and appropriate modelling capability are being developed.

Holistically, the ongoing coupled processes research and membership of the DECOVALEX project [332] are serving to demonstrate RWM's understanding of coupled processes in both a higher strength rock and a lower strength sedimentary rock [386, 387, 388, 389, 390, 391, 392], also see our S&T Plan [11] Tasks 399 and 400.

6.7 Co-location

For a facility in which ILW/LLW (and potentially DNLEU) and HHGW will be disposed of in separate disposal modules, that implement different EBS designs, there is the potential for co-location interactions to occur between the modules. Consideration of separation distances between disposal modules is needed as part of GDF design, as part of work contributory to the GDF safety case. Further research will be needed in relation to determining separation distances at a specific site; a separation distance of 500 m is currently assumed.

The current preferred approach to geological disposal is for a single co-located facility consisting of two distinct disposal systems for ILW/LLW (and potentially depleted, natural and low-enriched uranium (DNLEU)) and HHGW. It is anticipated that ILW/LLW and HHGW will be disposed of in separate disposal modules that implement different EBS designs appropriate to the different wastes and that share common access and surface facilities. These modules will be separated by an appropriate distance to ensure tat detrimental interactions cannot affect the performance of the disposal system. This subsection discusses the rationale for this ‘respect distance’.

This section considers the potential for co-location interactions to occur for a range of example disposal systems. It is based on work reported in references [393, 394] that considered THMCG coupled process issues related to a co-located GDF for the UK inventory for disposal. Reference [393] indicates that it is possible for ILW/LLW and HHGW disposal modules to be co-located without compromising key safety functions of different barrier components. Interactions are predicted to occur between the different disposal modules, but scoping calculations suggest that their magnitude will be relatively small or that they can be prevented or at least partially mitigated at the design stage. Note that in [393], a ‘respect distance’ of 500 m was assumed between the disposal modules, consistent with the assumptions made in earlier work [395]. On the basis of work reported in [393], it is inferred that, in most cases, the magnitude of the co-location interaction is likely to be within the uncertainty bounds that would be considered when evaluating the normal evolution of a disposal module that has not been co-located. However, it must be stressed that system performance, and hence the potential for co-location interactions, depends strongly on the properties of the host geological environment and the design of the GDF, neither of which are yet known for a UK GDF.

Higher-strength host rock example (HSR)
Scoping calculations in [393] have indicated that significant co-location interactions could potentially occur in HSR, primarily because it is possible for water or gas to be advected from one disposal module to the other if this is not precluded through design measures. However, it appears that these interactions could be prevented or largely mitigated through careful GDF design. Thermal interactions are unlikely to occur at respect distances of more than a few hundred metres.

It is possible in this example for fluid (water or gas) to be advected from one disposal module to the other on timescales that are of interest. Migration of gas in itself is not likely to result in an interaction that is likely to be detrimental to performance; GDF-derived gas is further considered in reference [6]. The pathways of interest comprise the natural fracture systems in both the host rock and the EDZ, should this provide a continuous pathway. These fluids can transport solutes and therefore there is the potential for chemical interactions to occur. However, it should be possible to minimise the impact of these chemical interactions through careful choice of layout and good sealing of the access tunnels that connect the disposal modules.

The scoping calculations suggest that it is unlikely that high pH fluids can be transported from the ILW/LLW disposal module to the HHGW disposal module during the resaturation period, even if the regional hydraulic gradient favours this direction of transport. Therefore the design of the GDF can focus on minimising long-term interactions. The evolution of the connecting tunnels and the performance of the low permeability seals that are emplaced within them will be important in preventing interactions.

Lower strength sedimentary host rock example (LSSR)
The arguments and scoping calculations presented in [393] suggest that hydrogeological, chemical and gas coupled process interactions are unlikely to be significant for this example because transport is dominated by diffusion. The timescale for transport between disposal modules is of the order of millions of years. It also seems unlikely that significant thermal and mechanical interactions will occur if the respect distance is more than a few hundred metres. Thus, so long as the EBS performs as intended (for example, seals perform as designed), co-location interactions are unlikely to have a detrimental impact on the long-term evolution of the GDF.

Evaporite host rock example
The properties of an evaporite host rock mean that the majority of the co-location interactions that have been identified are even less likely to occur in this host rock than they are in LSSR. The exception is thermal interactions, which are more likely to occur owing to the higher thermal conductivity of evaporite; however, we do not foresee any detriment to the disposal system's performance.

Longer-term changes
For longer-term change to result in a co-location interaction, it must either cause a significant change in the groundwater flow field or result in the creation of new pathways that link the disposal modules.

Glaciation has the potential to disrupt the system, both by changing the regional groundwater flow field and by changing the stress field, and hence the hydraulic conductivity, through loading effects. However, the next major glaciation is not expected before a 10^5 years' timescale, by which time the high heat output will have decayed significantly, thus reducing the impact of any interaction.

Fault reactivation also has the potential to create pathways through the geosphere that could, for example, potentially bypass seals. However, the UK is seismically quiet so it is extremely unlikely that fault reactivation could bypass all of the seals in the system and result in the creation of new pathways with length-scales of hundreds of metres.

Human intrusion has the potential to disrupt the GDF and result in the creation of new pathways between the disposal modules, for example, via a borehole that penetrates both modules and links them.

Recent RWM work on co-location
In [393], a 500 m separation was assumed, and on this basis interactions between modules were not inferred to be significant. More recent RWM work has considered how a separation distance could be determined, were it not sufficient to assume a separation distance of 500 m between GDF modules. Reference [396] considers the separation distance between co-located modules in the GDF. Reference [397] considers a methodology to determine a site-specific separation distance (and is covered by Task 394 in our S&T Plan [11]).

RWM therefore has the 'toolkit' necessary to consider THMCG interactions from GDF module to GDF module; to date this capability has been applied in a range of illustrative geologies, and is available to utilise on a site-specific basis. When RWM's programme is site-specific, it will be necessary to consider module separation, but whilst the programme is generic it is defensible to assume a 500 m separation for co-located modules (a 'respect distance') of the GDF (such a separation distance only has a small effect on the overall footprint of generic GDF designs for a range of illustrative geological environments).

6.8 Illustrative narratives - evolution of GDF and impacts on the geosphere

Narratives of the anticipated evolution for ILW/LLW and HHGW concepts in each of the three illustrative host rock types are presented.

This section presents illustrative narratives of the anticipated evolution for ILW/LLW and HHGW concepts in each of the three illustrative host rock types, considering the following time-frames:

- construction and operation
- early post closure
- late post closure.

Reference [398] considers the treatment of geosphere evolution in post-closure performance assessments, including the coupling of THMC processes. This report discusses the timescales and anticipated maximum distances over which the main THMC processes will operate in each of the illustrative host rocks. The conclusions are summarised in Figure 35 and Figure 36 respectively.

Figure 35 Timescales of the main Thermal, Hydrogeological, Mechanical, Chemical and Radionuclide transport processes [398].

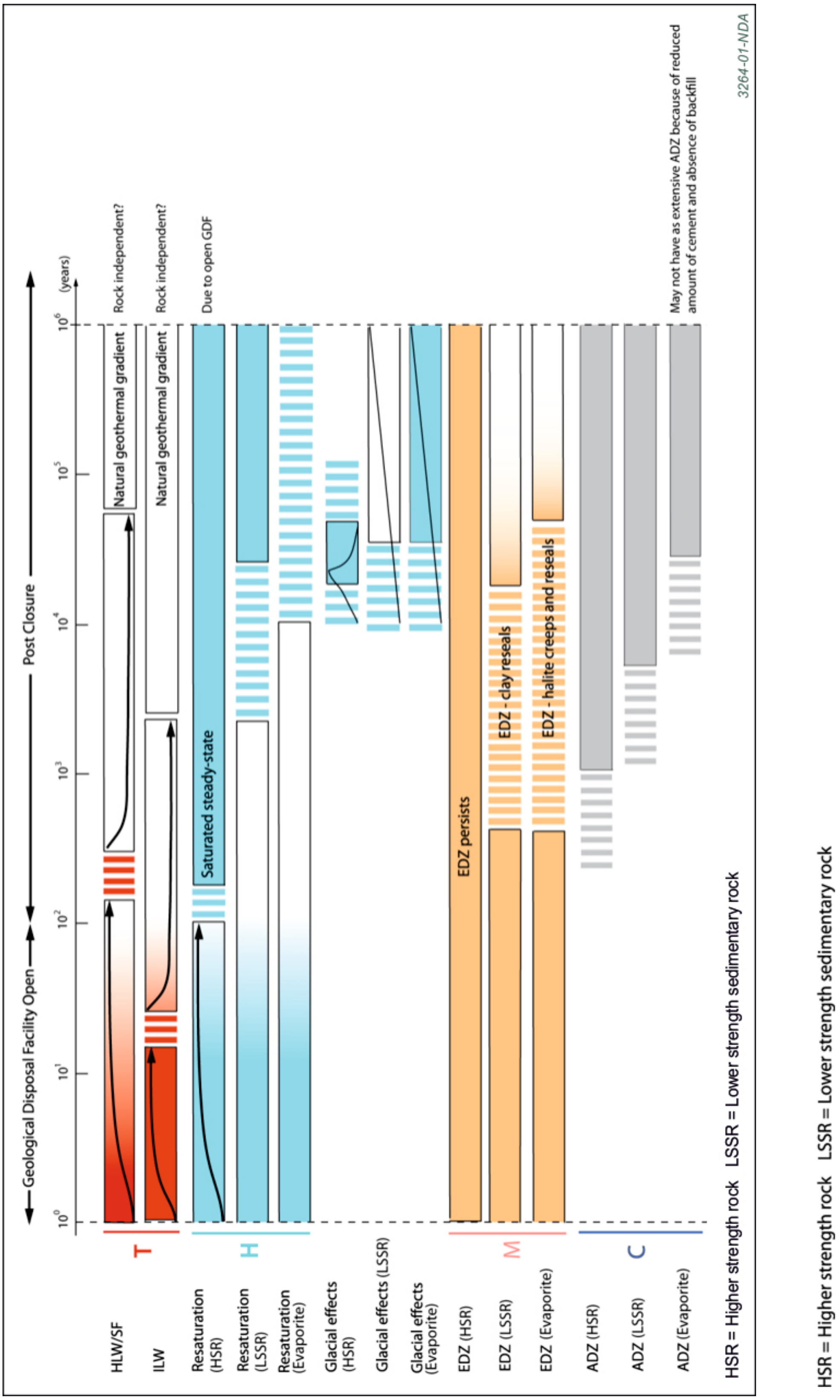
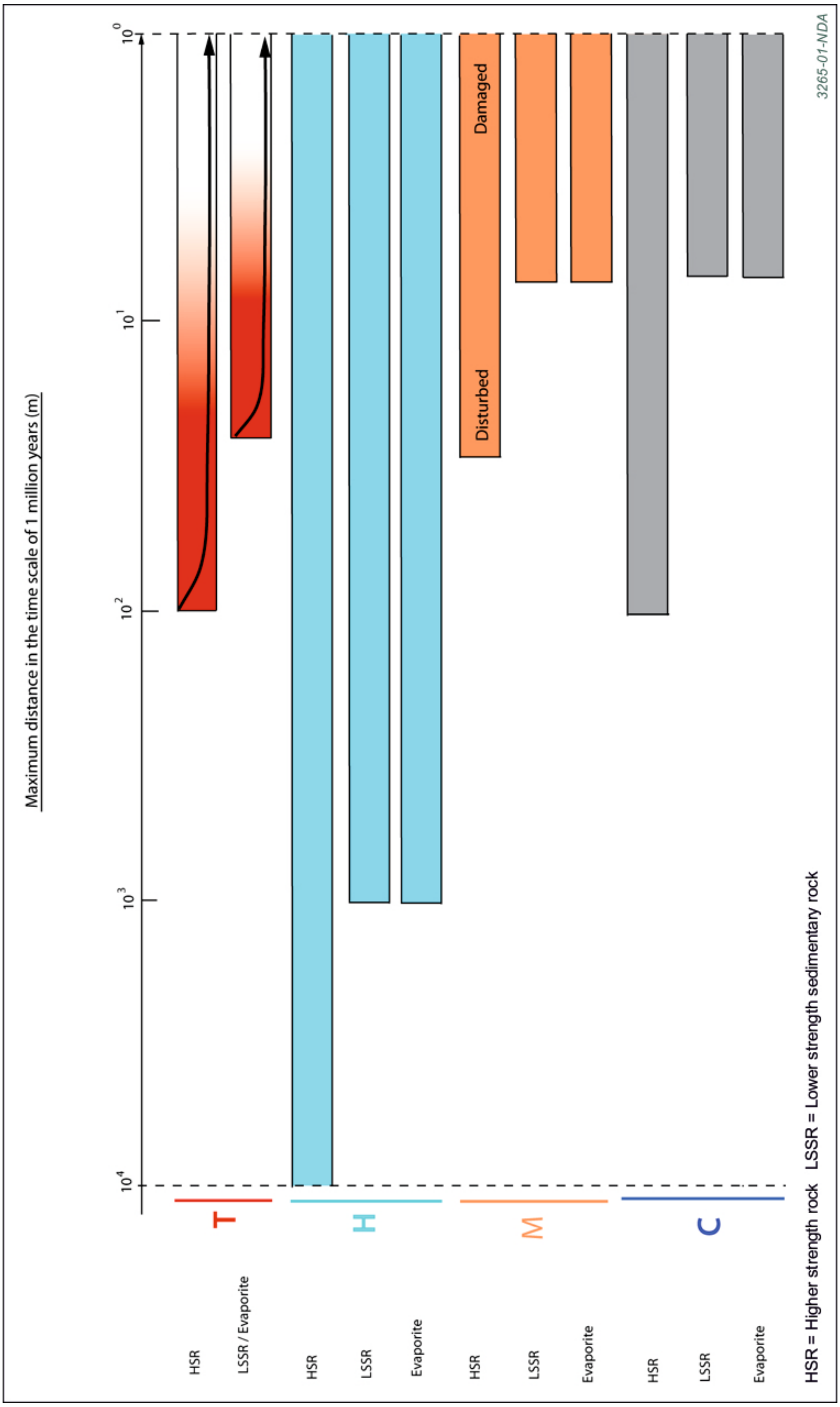


Figure 36 The maximum distance of influence of the main Thermal, Hydrogeological, Mechanical, Chemical and Radionuclide transport processes [398].



HSR = Higher strength rock LSSR = Lower strength sedimentary rock

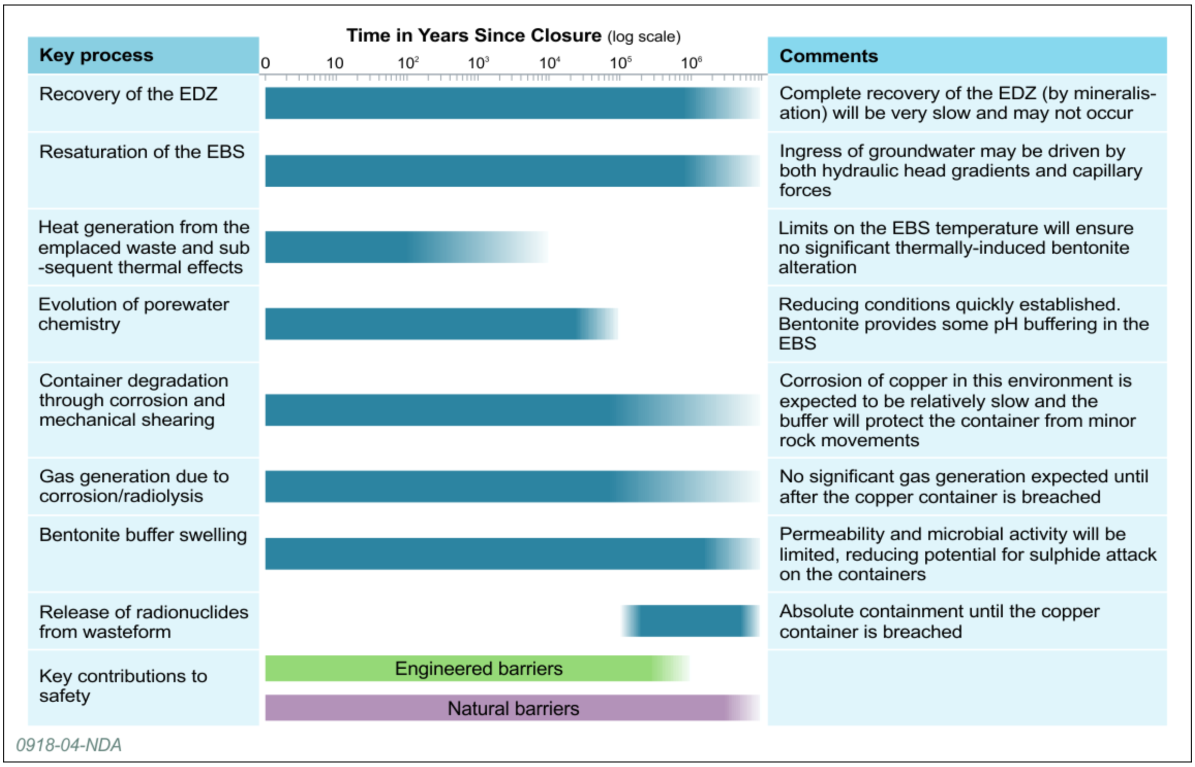
6.8.1 Evolution for an illustrative concept example for disposal of HHGW in a higher strength rock

Once resaturated, the bentonite buffer provides a low permeability barrier that protects a disposal container by limiting the transport to the container surface of species that might promote corrosion. The vast majority of the copper containers are expected to retain their physical integrity for a very long time. In the very long term retardation in the geosphere, through sorption and rock matrix diffusion, provides the main barrier to radionuclide transport.

This section provides a summary of the key steps in the near-field evolution of the illustrative concept for the disposal of HHGW and the impact this will have on surrounding higher strength host rock. The discussion draws on the description of expected evolution set out by SKB for the undisturbed performance of the KBS-3V concept [399, 400]. We have also drawn on understanding of the behaviour of this disposal concept, based on our work, completed previously as UK Nirex and as NDA RWMD [401, 402].

The approximate timescales over which key processes governing the evolution of this illustrative concept are illustrated in Figure 37. Many of the processes identified (such as container degradation, gas generation, buffer alteration and evolution of the host rock) are expected to occur very slowly over many thousands or tens of thousands of years. These processes can be described independently, but some are coupled to each other and need to be considered within the context of the disposal system.

Figure 37 Timeframes over which key near-field processes are expected to occur for the illustrative concept for disposal of HHGW in a higher strength host rock. T=0 is set as the time at which the GDF is closed.



Evolution of the geosphere during construction and operation of the GDF

An EDZ will be created as soon as excavation activities commence, due partly to excavation-related vibrations and partly to changes in the stress fields in the rock, which lead to brittle fracturing. The EDZ will have different mechanical and hydraulic properties to the intact host rock; it will be more extensively fractured, and consequently, will be more permeable, as well as exhibiting a lower fluid pressure in pores and fractures. Depending on the excavation technique and the nature of the site-specific geology, it may extend up to several tens of centimetres from the excavated region [403]. The redistribution of stress may cause rock spalling to occur and/or the reactivation of pre-existing fractures in the host rock.

The pre-existing hydraulic gradients present in a given geological environment will be disrupted by excavation of the GDF. Some fluid is likely to migrate along hydraulic gradients towards the engineered barrier system until the hydraulic potential of the GDF is restored to that of the surrounding host rock. Changes in the saturation of the host rock in response to changes in the hydraulic gradient are likely to occur relatively quickly, particularly if the host rock is significantly fractured.

Depending on the permeability of the rock and on the GDF's design, the chemistry of groundwater entering the engineered barrier system (EBS) (particularly the pH, redox potential and/or salinity) could potentially change as a result of infiltration of near-surface waters into deeper parts of the bedrock and/or upwelling of more saline waters from depth. Aerobic conditions will predominate in the host rock immediately adjacent to excavated surfaces, due to ingress of near-surface waters, and because the facility will be ventilated to the surface. Minor thermal perturbations of the host rock surrounding the excavated spaces may also occur, due to ventilation of these areas.

Although the EDZ may be able to seal through processes such as mineralisation of fractures there is unlikely to be significant sealing through rock creep, since higher strength rocks tend to be quite rigid. As a result, any recovery of the EDZ is likely to be quite slow. To counteract this, consideration can be given to sealing any significant EDZ fractures in disposal regions of the GDF (which might otherwise provide a rapid transport pathway), by filling them with some form of grout. If used, any cementitious grout materials may begin to react with groundwater and other components of the EBS, leading to increased pH of water in the engineered barrier system, and potentially affecting the presence of colloidal species and/or the sorption properties of the backfill, buffer and surrounding host rock. The onset of such interactions may be relatively quick, once the grout is emplaced.

The time taken to fully resaturate an individual deposition hole in a higher strength rock will vary between deposition holes, but is likely to be between a few years and several decades (or indeed longer), depending on the characteristics of the features that intersect the hole, such as the presence of minor fractures (resaturation on longer timescales is not unfeasible). Resaturation of the disposal tunnels will take longer (probably decades to centuries) because there is a larger volume of pore space to be resaturated. Thus, the early deposition holes, and possibly some of the early disposal tunnels, are likely to be fully resaturated before final closure of the GDF.

HHGW waste will initially give off significant quantities of heat as a result of the decay of the short-lived component of the inventory. While the disposal tunnels are open we will use the ventilation system to ensure that temperatures in the open parts of the GDF remain within specified limits. Once a disposal tunnel has been sealed, the temperature in the buffer and in the surrounding rock may rise several tens of degrees above ambient. Thermal constraints are likely to be a significant factor determining package spacing and underground layout.

The final stage of the closure engineering is the backfilling of the various access tunnels and shafts and emplacement of the main low-permeability seals. Ideally, the permeability of the seals should be no higher than the rock in which they are emplaced.

During this early period of GDF evolution, the waste packages, which are protected by the bentonite buffer, will provide complete containment of the waste.

Early post-closure evolution

During this period the HHGW gives off significant quantities of heat until the short-lived component of the radionuclide inventory has decayed. As a result, the temperature of the surrounding rock may rise to several tens of degrees above ambient before slowly decreasing. The peak temperature (140-160^{o}C) is likely to occur within a few decades of waste emplacement, but we expect temperatures to remain above ambient for up to 10,000 years, depending on the waste inventory. The elevated temperatures will affect the solubility of minerals in the bentonite component of the EBS, and hence the porewater pH and mineralogy, leading to spatial variation in porewater characteristics migrating into the host rock, depending on the thermal regime.

The chemical conditions in the surrounding host rock are likely to slowly return to values close to undisturbed conditions over tens of hundreds of years, depending on the transport properties of this region, although the persistence of different conditions on the local scale cannot be discounted. Hydraulic properties will also slowly recover to equilibrium with the surrounding environment once the engineered barrier system is saturated and no longer exerts a hydraulic gradient on the host rock.

HHGW provides a number of additional technical challenges over and above those associated with the disposal of low-heat-generating waste. The heat generated from heat-generating waste will lead to a temperature rise in the surrounding rocks. These materials will expand as a result of the temperature rise, and this may lead to an uplift of the ground surface above the GDF. The magnitude of any uplift depends on the heat output of the waste, the design of the GDF (in particular, its footprint and depth) and key properties (the thermal conductivity, specific heat capacity, density, thermal expansion coefficient and Poisson's ratio) of the GDF materials and surrounding rocks. Variations in thermal conductivity and expansivity in the overburden, and the scope for accommodation of any expansion in the near-field by compressional accommodation in the over- and under-burden, are also important site-specific aspects affecting the magnitude of any uplift.

Representative values and ranges for key parameters have been identified for the potential host rocks in the generic concepts for the GDF under consideration by RWM. The magnitude of the uplift has been calculated for representative parameter values in [404] as 0.3m for the GDF in higher strength rock, occurring at a time of about 10,000 years (this calculation neglects site-specific aspects as could affect the magnitude of uplift).

The potential implications of thermal uplift will be considered in future RWM work (see Task 351 [11] for further information); this will include a consideration of the effects of thermal expansion on, for example, rock properties, fracture development or enhancement.

Late post-closure evolution

In the very long term (many hundreds of thousands to millions of years) the EBS is not expected to provide full containment, although some of the copper containers may remain intact. Any radionuclides that are released from the engineered barrier system will be retarded, and potentially contained, in the geosphere.

Retardation in the geosphere, through sorption and rock matrix diffusion, now provides the main barrier to limit the rate of release to the biosphere, and will be sufficient to provide containment for some radionuclides. Over these very long timescales, the potential impact of various "natural" disturbances or transients that can arise from the effects of global climate events need to be considered (for example, glaciation or global warming events [399, 405]).

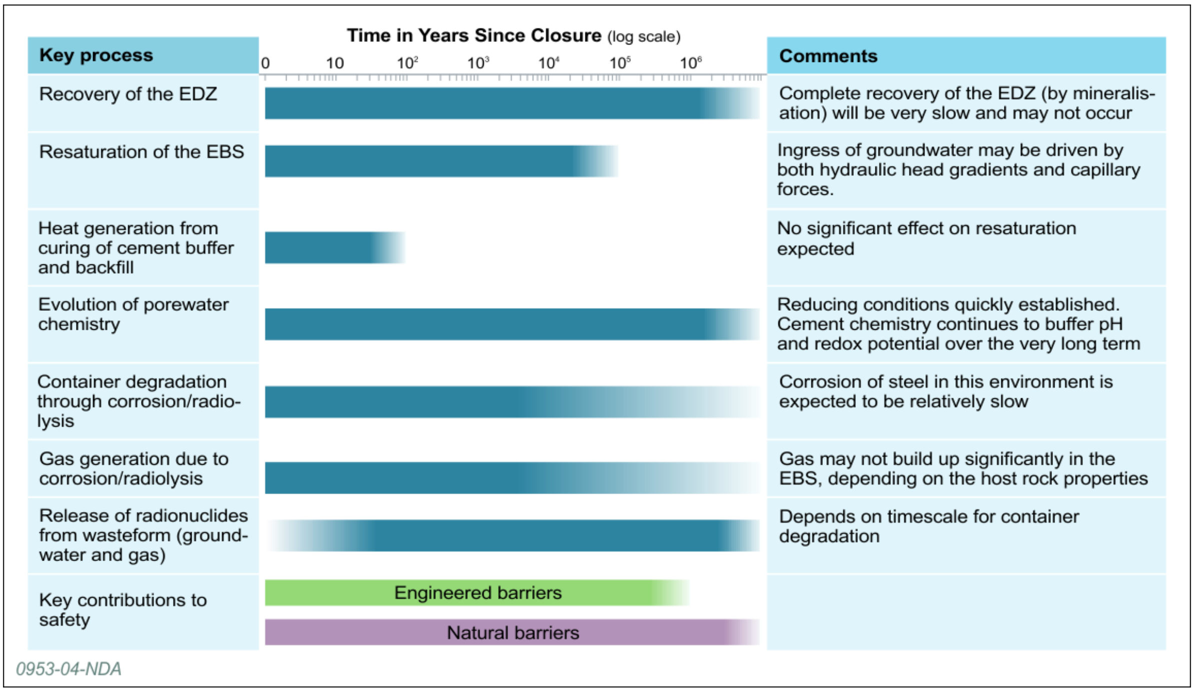
6.8.2 Evolution for an illustrative concept example for disposal of ILW / LLW in a higher strength rock

In this concept, ILW and LLW are encapsulated in cementitious grout in stainless steel containers and placed in disposal modules. These are backfilled with a cementitious material designed to provide a long-term chemical barrier. In the very long term, the rock will retard the migration of radionuclides through sorption and rock matrix diffusion.

This section provides a summary of the key steps in the near-field evolution of the illustrative concept for the disposal of ILW / LLW and the impact this will have on surrounding higher strength host rock.

The approximate timescales over which key processes dominating during the evolution of this illustrative concept are expected to occur in HSR are illustrated in Figure 38. Many of the processes identified (for example, cement evolution and gas generation) are expected to occur very slowly over many thousands or tens of thousands of years. These processes can be described independently, but they are strongly coupled to each other.

Figure 38 Timeframes over which key near-field processes are expected to occur for the illustrative concept for disposal of LHGW in a higher strength host rock. T=0 is set as the time at which the GDF is closed.



Evolution during construction and operation of the GDF

An EDZ will be created as soon as excavation activities commence, due partly to excavation-related vibrations and partly to changes in the stress fields in the rock, which lead to brittle fracturing. Evolution of the EDZ will be fairly similar to that described above for the illustrative HHGW concept in a higher strength host rock. The major difference relates to the compatibility of any cement-based grouting or fracture filling materials with the cementitious backfill. Materials considered for fracture grouting are not likely to affect either the host rock properties (since the host rock is not predominately clay-based) or affect the function of the chemical buffer provided by the backfill. Any pH plumes arising from fracture grouting materials in the EDZ are likely to be minor in comparison to the impact of chemical conditions provided by any backfill.

During the operational period, the ILW / LLW vaults and the access tunnels will be maintained in a dry and ventilated state. This will result in some desaturation of the host rock around the excavations. The rock immediately adjacent to the excavations may also undergo chemical changes as a result of oxidation reactions, or as a result of reactions with materials, most likely concretes, that are used to provide structural support to the excavations. For example, fracture zones might be grouted to reduce water inflows or lined with sprayed concrete to reduce the potential for spalling and/or rock falls. Some of the ensuing reactions may contribute to the sealing of fractures in the EDZ referred to above. The presence of the GDF that is maintained in an open and ventilated state for many decades could, through the flow it induces, potentially lead to changes in the composition of the groundwater in the surrounding host rock. For example, upconing of more saline water from depth is considered to be a possibility in Scandinavia [399]. Minor thermal perturbations of the host rock surrounding the excavated spaces may also occur, due to, for example, exothermic reactions related to the curing of cementitious backfill material.

Early post-closure evolution

Following closure, the ILW / LLW disposal area will start to resaturate. The time taken for the disposal vaults to resaturate fully will depend on the properties of the host rock, but in a typical higher strength host rock it is expected to be of the order of a few years to a few centuries [406], depending on site-specific characteristics. The incoming groundwater will rapidly equilibrate with the NRVB, resulting in the development of alkaline conditions. Corrosion reactions will result in the establishment of reducing conditions.

Although high pH and reducing conditions will limit the rate of corrosion processes [2, 6], gas (predominantly hydrogen, but also some carbon dioxide and methane) will be generated, mostly by the corrosion of Magnox and aluminium present in the waste, but also from the corrosion of the various steel components and the degradation of organic materials. The carbon dioxide will react with the cementitious backfill [6, 406]. Some carbon dioxide will dissolve in the groundwater, but it is likely that a free gas phase will form, dominated by hydrogen. However, it is expected that gas will be able to escape relatively easily into the host rock [6], although its presence may slightly reduce the rate of resaturation. Depending on the gas transport properties of the geosphere at the site, limited amounts of this free gas may reach the surface.

Once the disposal vault resaturates, small amounts of the ILW / LLW inventory will begin to be released, in dissolved form, into the backfill. It is expected that the quantity of cementitious backfill used in the ILW / LLW disposal area will be sufficient to maintain alkaline reducing conditions for at least a hundred thousand years. The wasteform and the chemical barrier provided by the backfill are both important barriers limiting the rate of release of contaminants into the geosphere.

Throughout this period, the near-field porewater will be conditioned to high pH by the dissolution of cement. An alkaline disturbed zone (ADZ) is expected to develop around the ILW / LLW disposal area as a result of reactions between the host rock and the conditioned porewater. The resulting mineral dissolution and precipitation may alter the hydrogeological properties of the host rock around the GDF. It is expected that there will be a net decrease in porosity and permeability as fractures, especially those in the EDZ, become filled with new, relatively high volume, minerals.

Late post-closure evolution

In the very long term (many hundreds of thousands to millions of years) the EBS is not expected to provide complete containment. With time, the wasteforms and the NRVB will be altered through reaction with the groundwater and those radionuclides that have not decayed within the EBS may be released to the host rock. Eventually, the alkaline disturbed zone in the surrounding rock will become less extensive.

On these very long timescales the potential impact of various 'natural' disturbances or transients that can arise from the effects of global climate events need to be considered (for example, glaciation or global warming events [405]).

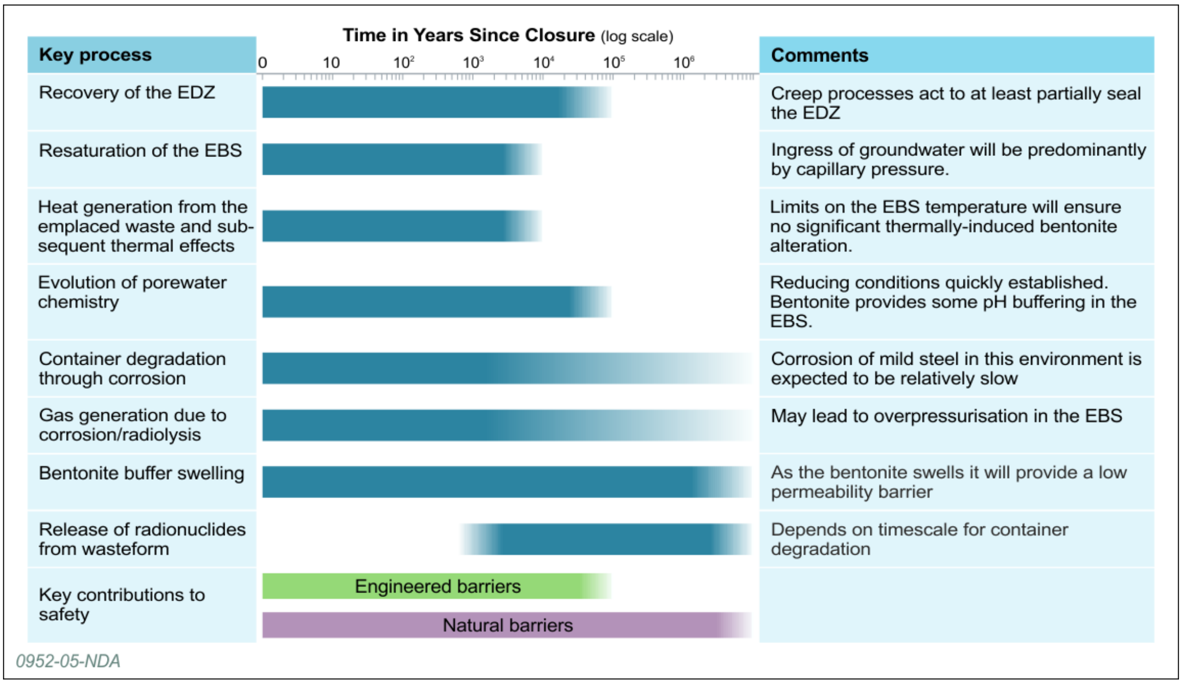
6.8.3 Evolution for an illustrative concept example for disposal of HHGW in a lower strength sedimentary rock

In this concept, gradual corrosion of the disposal containers will occur as resaturation proceeds. Once containers eventually fail, the low permeability rock will provide an important barrier to the migration of radionuclides.

This section provides a summary of the key steps in the near-field evolution of the illustrative concept for the disposal of HHGW and the impact this will have on surrounding lower strength sedimentary host rock.

The approximate timescales over which the key processes dominating during the evolution of this illustrative concept are expected to occur in LSSR are illustrated in Figure 39. Many of the processes identified (such as container degradation, gas generation and buffer alteration) are expected to occur very slowly over many thousands or tens of thousands of years. These processes can be described independently, but they are strongly coupled to each other.

Figure 39 Timeframes over which key near-field processes are expected to occur for the illustrative concept example for disposal of HHGW in a lower strength sedimentary host rock. T=0 is set as the time at which the GDF is closed.



Evolution during construction and operation of the GDF

Construction activities will lead to the formation of an excavation disturbed zone (EDZ) around the tunnels and vaults. The properties of the EDZ will evolve, partly in response to the clay-dominated host rock drying out during the operational phase, and partly because lower strength sedimentary rocks can exhibit creep, particularly if they are poorly indurated. The extent of the EDZ and its characteristics will depend on the geotechnical characteristics of the host rock and the in situ stress, both of which are site and depth specific, and on the excavation technique and any excavation support that is installed. In lower strength sedimentary host rocks, such as indurated mudrock, the EDZ generally extends for a distance of up to a tunnel's radius [327]. In Opalinus Clay, the EDZ is expected to extend about 2 m from the roof and floor of the disposal tunnels [407]. It is expected that damage associated with the EDZ will result in localised changes to hydrogeological properties. Creep, resulting in the self-sealing of fractures and to some degree the excavations themselves, is likely to be important in a lower strength sedimentary host rock [407]. This property is important for performance because it means that the ability of the EDZ to conduct water and contaminants will tend to decrease with time following closure of a disposal vault or tunnel. The timescale for self-sealing depends on the physical properties of the host rock, the stress regime and the type of engineering support provided. For a poorly-indurated rock, self-sealing and EDZ recovery may be rapid, taking a few years or less to close fractures in the EDZ. However, for more indurated clay rocks, self-sealing could take many centuries or thousands of years, and the disturbed host rock may never completely return to its undisturbed state. The rate and extent of self-sealing are also influenced by the degree to which the rock has become dehydrated.

During this period 'operational' seals may be placed at the entrances to waste-filled disposal tunnels. Given that filling a disposal tunnel will take only a few months, some disposal tunnels will be sealed very early in the operational phase of the GDF. However, the low permeability of the host rock will limit the degree to which the disposal areas are able to resaturate during the operational period. Assuming that the excavated cavities will be backfilled progressively during operations and/or at the time of closure, when the GDF is finally sealed, there will be very little remaining void space. The sealing and backfilling materials will have a combination of mechanical properties that will enable them to withstand the stresses caused by creep of the host rock during the operational phase. Seals and backfills using swelling clays such as bentonite will begin to swell, thereby exerting a pressure that will oppose the inward convergence of the host rock. By limiting long-term creep of the host rock the EBS prevents macroscopic deformation, including fracturing, and enables a homogeneous stress state to be re-established. Such processes may occur during the construction and operational period and throughout the post-closure period.

Early post-closure evolution

Following closure, the resaturation process described above will continue, and eventually complete. For the Nagra concept, modelling work suggests resaturation may take from ~100 years to many hundreds of years, due to the low hydraulic conductivity of the Opalinus Clay [407].

In addition to the swelling that occurs on resaturation, interaction with the host rock groundwater will result in some minimal changes to the physical and chemical properties of the bentonite buffer. Exposure of these minerals to hyperalkaline porewater as a result of cement leaching (from engineering support materials) may result in small regions of the buffer with reduced swelling pressure. EBS porewater redox conditions will tend to be reducing, controlled by the presence of iron in engineered materials, together with a neutral to mildly-alkaline pH provided by the weak buffering capacity of the bentonite component of the EBS and minerals contained in the host rock.

The waste will give off significant quantities of heat until the short-lived component of the inventory has decayed. As a result the temperature of the surrounding rock may rise by several tens of degrees before slowly decreasing. The maximum temperature in the EBS of 140-160°C [407] is likely to occur at the container's surface within a few years of waste emplacement and temperatures in the HHGW disposal area will remain elevated for over

1000 years. Temperatures in the surrounding rock will also be elevated, generally to values much lower than the container surface, although a profile of increased temperature is expected. It is expected that temperatures should have returned to their undisturbed values before the container stops providing containment.

HHGW provides a number of additional technical challenges over and above those associated with the disposal of low-heat-generating waste. The heat generated from heat-generating waste will lead to a temperature rise in the surrounding rocks. These materials will expand as a result of the temperature rise, and this may lead to an uplift of the ground surface above the GDF. The magnitude of any uplift depends on the heat output of the waste, the design of the GDF (in particular, its footprint and depth) and key properties (the thermal conductivity, specific heat capacity, density, thermal expansion coefficient and Poisson's ratio) of the GDF materials and surrounding rocks. Variations in thermal conductivity and expansivity in the overburden, and the scope for accommodation of any expansion in the near-field by compressional accommodation in the over- and under-burden, are also important aspects affecting the magnitude of any uplift.

Representative values and ranges for key parameters have been identified for the potential host rocks in the generic concepts for the GDF under consideration by RWM. The magnitude of the uplift has been calculated for representative parameter values in reference [404] as 0.85m for the GDF in lower strength sedimentary rock, occurring at a time of about 15,000 years (this calculation neglects site-specific aspects as could affect the magnitude of uplift).

Note that the study reported in [404] did not consider creep (or other plastic deformation); this is likely to mean that the uplift would be lower than that calculated here. This is an important caveat on the calculated uplift. Creep and plastic failure mechanisms can be dilatant, that is, they can give rise to increases in rock volume, as well as giving rise to compaction and providing a means to distribute the thermally expanded rock over a larger volume. Therefore these non-elastic effects may not only act to decrease uplift, but may locally increase it.

The potential implications of thermal uplift are being considered in ongoing RWM work (see reference [11], Task 351 for further information).

Despite the relatively benign chemical environment and diffusion-dominated solute transport within the bentonite buffer, corrosion of the carbon steel disposal container will occur [407] and hydrogen gas will be generated. Since there is little capacity to accommodate gas in the EBS of this disposal concept, and given the low permeability of the host rock, the gas pressure is expected to accumulate, and eventually cause two-phase flow of gas (dissolved in groundwater and as a free gas phase) to occur in the EBS and the host rock [407].

During this period, the engineered barriers are degrading very slowly as a result of interaction with the groundwater and with each other. However they remain sufficiently intact that they are able to perform their intended safety functions fully. The low-permeability host rock contributes to the durability of the EBS by providing a stable chemical environment and limiting the rate of water flow through the EBS. It is important to note that the buffers and backfills must be fully resaturated before they can function properly, and a lower than expected resaturation rate (such as an unexpectedly low groundwater flow in such a low permeability environment) may prevent the barrier functions from becoming established on the expected timescale.

The low permeability of lower strength sedimentary rock, in which solute transport is predominantly diffusive, provides an important barrier to the migration of radionuclides that are released from the engineered barrier system.

Late post-closure evolution

In the very long term in a lower strength sedimentary host rock environment, groundwater flow will be diffusion dominated and so migration of radionuclides away from the engineered barrier system will be relatively slow. On these very long timescales consideration of the potential impact of various ‘natural’ disturbances or transients which can arise from the effects of global climate events is required (for example, glaciation or global warming events).

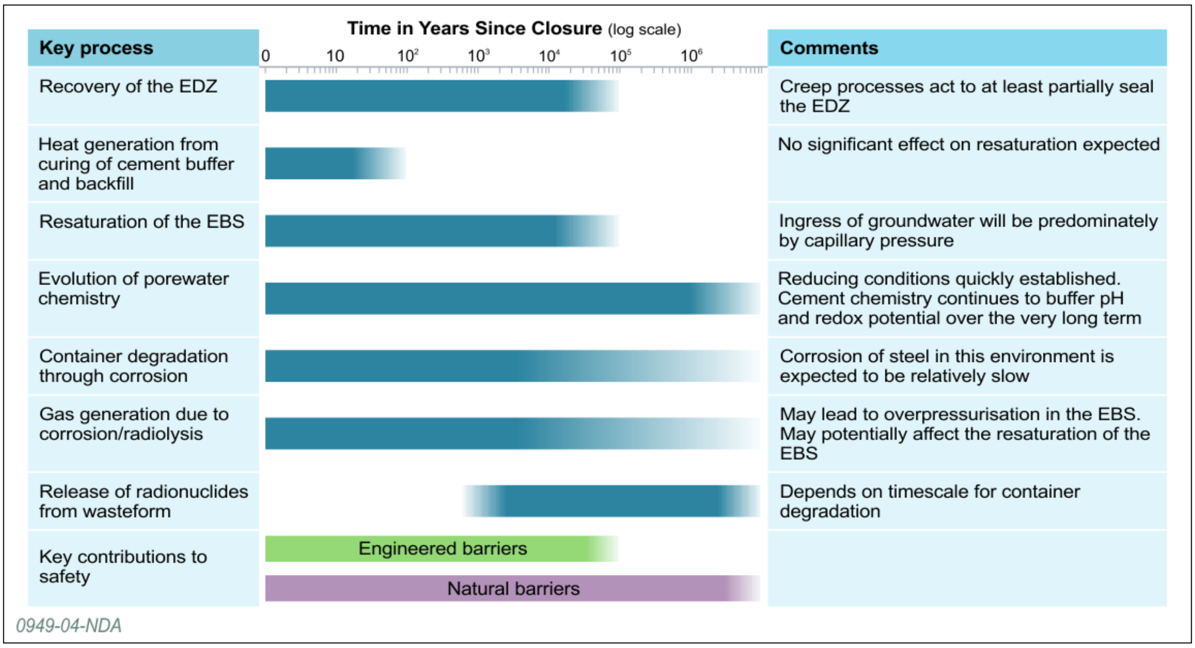
6.8.4 Evolution for an illustrative concept example for disposal of ILW / LLW in a lower strength sedimentary rock

In this concept, following resaturation, higher pH conditions will develop that limit solubility and promote the precipitation of radionuclides. The low-permeability host rock limits transport of dissolved contaminants.

This section provides a summary of the key steps in the near-field evolution of the illustrative concept for disposal of ILW / LLW and the impact this will have on surrounding lower strength sedimentary host rock. The discussion draws in particular on the description of expected evolution set out by Nagra [407, 408].

The approximate timescales over which key processes dominating during the evolution of this illustrative concept are expected to occur in LSSR are illustrated in Figure 40.

Figure 40 Timeframes over which key near-field processes are expected to occur for the illustrative concept example for disposal of ILW / LLW in a lower strength sedimentary host rock. T=0 is set as the time at which the GDF is closed.



Many of the processes identified (such as evolution of the backfill mortar) are expected to evolve very slowly over many thousands or tens of thousands of years. These processes can be described independently; however some may be coupled to each other and therefore should be considered within the context of the disposal system.

Evolution during construction and operation of the GDF

Construction activities will lead to the formation of an excavation disturbed zone around the tunnels and vaults. The properties of the EDZ will evolve, partly in response to the clay-dominated host rock drying out during the operational phase of the disposal facility, and partly because lower strength sedimentary rocks exhibit creep, particularly if they are poorly indurated. The extent of the EDZ and its characteristics will depend on the geotechnical characteristics of the host rock and the in situ stress, both of which are site and depth specific, and depend on the excavation technique and any excavation support that is installed. In lower strength sedimentary host rocks, such as indurated mudrock, the EDZ may extend for a distance of up to a tunnel's radius [327]. The damage associated with the EDZ is expected to result in localised changes to hydrogeological properties. Creep, resulting in the self-sealing of fractures, and to some extent, the excavations themselves, is likely to be significant in lower strength sedimentary host rock. For a poorly indurated rock, self-sealing and EDZ recovery may be rapid, taking a few years or less to close fractures in the EDZ. However, for more indurated clay rocks, self-sealing could take many centuries or thousands of years, and the disturbed host rock may never completely return to its undisturbed state. The rate and extent of self-sealing is also influenced by the degree to which the rock has become dehydrated.

Backfilling of the disposal vault will increase the temperature through cement hydration and will bring additional water into contact with the waste packages, although some water will have already been introduced, predominantly in the cement encapsulant.

As the backfilled disposal vault resaturates, any oxygen will be consumed by corrosion and other processes, returning the host rock to anaerobic conditions. Alkaline conditions will develop as the incoming groundwater equilibrates with the cementitious backfill.

As soon as they have been sealed, the ILW/LLW disposal vaults will start to resaturate, albeit slowly, while waste is emplaced in adjacent vaults. Given that filling a disposal vault or tunnel may take only a few months and, depending on the backfilling strategy adopted, some disposal vaults and tunnels may be sealed very early (within the operational phase). However, the low permeability of the host rock will limit the extent to which the disposal areas are able to resaturate during the operational period.

Early post-closure evolution

Following closure of the GDF the resaturation process described above will continue, and eventually complete. This is expected to take ~500 years, but it could potentially take much longer for the GDF to resaturate fully and for stable, homogeneous conditions to become established, depending on the hydraulic conductivity of the host rock [408]. Gas generated due to corrosion will hinder resaturation by increasing the pressure in the EBS and the immediately adjacent host rock.

Significant volumes of gas (mostly hydrogen, but also some methane and carbon dioxide) may be generated in the ILW / LLW disposal vaults from the corrosion of the various steel components and the degradation of organic materials in the waste [407]. The gas generation rate may be limited by the availability of water, that is, it is expected to be low in the lower permeability lower strength sedimentary host rocks. Carbon dioxide is expected to either dissolve or react with the cementitious backfill. Other gases are likely to accumulate in the EBS within pore spaces in the backfill, initially dissolved in porewater, then as a free gas phase as the concentration increases above the solubility limit. Gas migration through the host rock via diffusion is relatively slow, so it is expected that some pressurisation in the EBS will occur as a free gas phase develops. If the gas pressure exceeds the rock entry pressure, free gas could enter the host rock as a result of pore dilation and micro-fissuring [407, 408]. The Gas Status Report [6] describes the processes by which free gas may be able to migrate into a lower strength sedimentary host rock once sufficient over-pressures have developed within the GDF. The Nagra concept is designed to ensure that gas pressures cannot build up to the extent that they might damage the integrity of the engineered barriers or the host rock. For example, the high porosity backfill in the vaults is designed to mitigate the localised build-up of excessive gas pressures and suitable seals may allow the passage of gas whilst restricting the flow of water.

The low-permeability host rock contributes to the durability of the EBS by providing a stable chemical environment and limiting the rate of water flow through the EBS. The majority of the degradation reactions that affect the engineered barriers are water mediated, so limiting the volume of water flowing through the EBS both limits the rate of barrier degradation and limits the rate at which dissolved contaminants can be transported away from the waste packages.

An alkaline disturbed zone is likely to form in the host rock around the ILW / LLW disposal area, although its extent is likely to be limited due to the limited permeability of the rock and minimal water flow. Reactions between cementitious water and the clay minerals of the host rock are expected to result in the precipitation of new minerals that will block the host rock porosity and result in a decrease in permeability; these minerals will also seal any EDZ fractures that have not self-sealed as a result of creep. This will reduce radionuclide transport via the groundwater, but will not have a significant effect on gas migration.

Late post-closure evolution

With time, the wasteforms and the cementitious backfill will alter through reaction with the groundwater and may be disrupted as a result of rock creep and associated compaction. Those radionuclides that have not decayed within the waste packages and engineered barrier system may be released to the host rock.

In the very long term (many hundreds of thousands to millions of years) the EBS is not expected to provide containment. On these very long timescales, consideration will need to be given to the potential impact of various “natural” disturbances or transients that could arise from the effects of global climate events (for example, glaciation or global warming events).

6.8.5 Evolution for an illustrative concept example for disposal of HHGW in an evaporite host rock

An EDZ in evaporite host rock, and creep, will need to be managed during the operational phase, as redistribution of stresses may lead to brittle fracturing and subsequent rock fall. After closure, creep of the host rock will rapidly fill voids and seal fractures introduced by the disposal system. By the time significant waste package degradation has occurred complete containment will be provided by the host rock.

This section provides a summary of the key steps in the near-field evolution of the illustrative concept example for disposal of HHGW and the impact this will have on surrounding evaporite host rock.

The behaviour of a disposal system in an evaporite is dominated by the coupled processes of deformation of the rock surrounding the excavation, fluid movement (if any), thermal effects and wasteform/waste package degradation. Each of these processes can be described independently, but they are strongly inter-dependent; the extent to which each process occurs will be affected by the others [340].

The approximate timescales over which key processes dominating during the evolution of this illustrative disposal concept are expected to occur in an evaporite are illustrated in

Figure 41. Many of these processes occur simultaneously and are most pronounced during the early post-closure period.

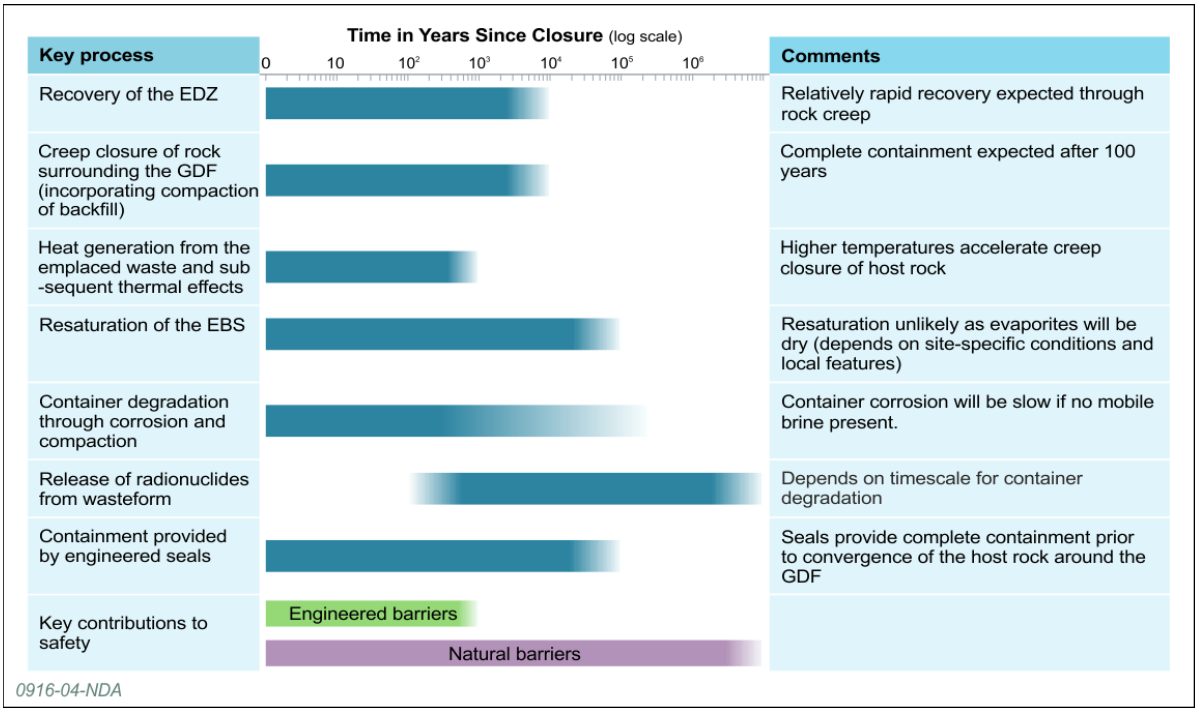
Evolution during construction and operation of the GDF

An EDZ will be created as soon as excavation activities commence as a result of changes in the stress fields in the rock, which will lead to brittle fracturing. Rock spalling may also occur during excavation and/or construction. The EDZ will have different mechanical and hydraulic properties to the intact host rock; it will be more extensively fractured, and consequently, will be more permeable, as well as exhibiting a lower pore pressure. It is likely to extend no more than a few metres from the excavated region [409].

Salt creep will begin immediately following excavation, driven by the presence of a differential stress due to the creation of void spaces. Scraping of vault walls, ceilings and floors will be necessary during construction and emplacement to keep facilities open until operations are complete [340]. During construction and operation, any heat generated in the GDF will be dissipated by ventilation and by heat transfer through the surrounding thermally-conductive host rock.

Oxidising conditions will predominate in the engineered barrier system during this phase, but these will quickly revert to reducing conditions once the GDF is closed.

Figure 41 Timeframes over which key near-field processes are expected to occur for the illustrative concept example for disposal of HHGW in a halite host rock. T=0 is set as the time at which the GDF is closed.



Early post-closure evolution

Rock creep around the GDF will continue; the geological barrier will provide increased containment in its own right as time progresses.

Early on, the impermeable components of the shaft seals (such as possibly concrete, clay and asphalt) will be important to prevent inflow of water from the surface (and potentially from overlying formations) to the GDF, as well as to prevent rapid radionuclide transport to the accessible environment. Compaction and creep of crushed salt components of tunnel and shaft seals due to rock creep will render their permeability similar to that of the host rock within approximately 200 years. This will prevent water circulation in the disposal region and releases to the accessible environment.

The crushed salt backfill will compact under the influence of surrounding rock creep. Over time, porosity in the crushed salt will be eliminated and eventually the backfill will assume the same properties as the surrounding host rock, merging with it to provide a continuous barrier of low-permeability salt.

Relatively rapid recovery of the EDZ is expected through rock creep, which will enable fractures to seal. The recovery of the EDZ around the waste shaft will be aided by the resistance of rigid components of the shaft-sealing system. The EDZ around the shaft is therefore not expected to provide a continuous pathway for fluid flow, either from the surface, or out of the engineered barrier system. Later, the rigid resistance of compacted backfill in the disposal tunnels will also encourage sealing of the fractures surrounding the GDF.

The waste will give off significant quantities of heat until the short-lived component of the radionuclide inventory has decayed. Rock creep is accelerated at higher temperatures. This will encourage more rapid recovery of the EDZ and hence, sealing of the GDF while temperatures are elevated. As a result, complete containment through rock creep is expected after several hundred years for heat-generating wastes, whereas this process is expected to take several thousand years for non-heat-generating wastes. Of course, there will also be spatial variations in the creep rate, depending on proximity to heat-generating waste. Higher temperatures, coupled with increased rock creep, will also increase the convergence rate of the crushed salt backfill.

HHGW provides a number of additional technical challenges over and above those associated with the disposal of low-heat-generating waste. The heat generated from heat-generating waste will lead to a temperature rise in the surrounding rocks. These materials will expand as a result of the temperature rise, and this may lead to an uplift of the ground surface above the GDF. The magnitude of any uplift depends on the heat output of the waste, the design of the GDF (in particular, its footprint and depth) and key properties (the thermal conductivity, specific heat capacity, density, thermal expansion coefficient and Poisson's ratio) of the GDF materials and surrounding rocks. Variations in thermal conductivity and expansivity in the overburden, and the scope for accommodation of any expansion in the near-field by compressional accommodation in the over- and under-burden, are also important aspects affecting the magnitude of any uplift.

Representative values and ranges for key parameters have been identified for the potential host rocks in the generic concepts for the GDF under consideration by RWM. The magnitude of the uplift has been calculated for representative parameter values in [404] as 1.15m for the GDF in an evaporite, occurring at a time of about 5,000 years (this calculation neglects site-specific aspects as could affect the magnitude of uplift).

The potential implications of thermal uplift are being considered in ongoing RWM work (see [11] Task 351 for further information).

As the heat output from the waste falls, adjacent rock will cool. The implications of cooling on evolving rock properties will need to be considered.

As diffusive transport of chemical species dominates in rock salt, due to its very low permeability, any resaturation of the GDF constructed in such a host rock will be a very long-term process. Thermally-driven brine pocket migration towards the GDF may occur, dependent on site-specific properties of the rock salt. Gas pressurisation, due to waste package degradation, may provide pathways for any fluid present to move outward from the excavated region, since pressurisation may cause fracturing of more brittle host rock layers. However, in such a geological environment gas generation will be limited by the availability of water.

Late post-closure evolution

After several thousands of years, the engineered barriers are likely to be significantly degraded. Containers may be breached due to compaction, enhanced by rock creep, and as a result of various chemical degradation processes. However, by the time significant waste package degradation has occurred and other engineered barriers have also failed, complete containment of the waste in the GDF will be provided by the host rock.

An important requirement for long-term safety is to have ensured, through the site selection and disposal system design processes, that there is no mechanism for preferential transport of fluid (and radionuclides) to the surface. If these design and siting requirements are satisfied, then no radionuclide release is expected for a normal (undisturbed) disposal scenario.

6.8.6 Evolution for an illustrative concept example for disposal of ILW / LLW in an evaporite host rock

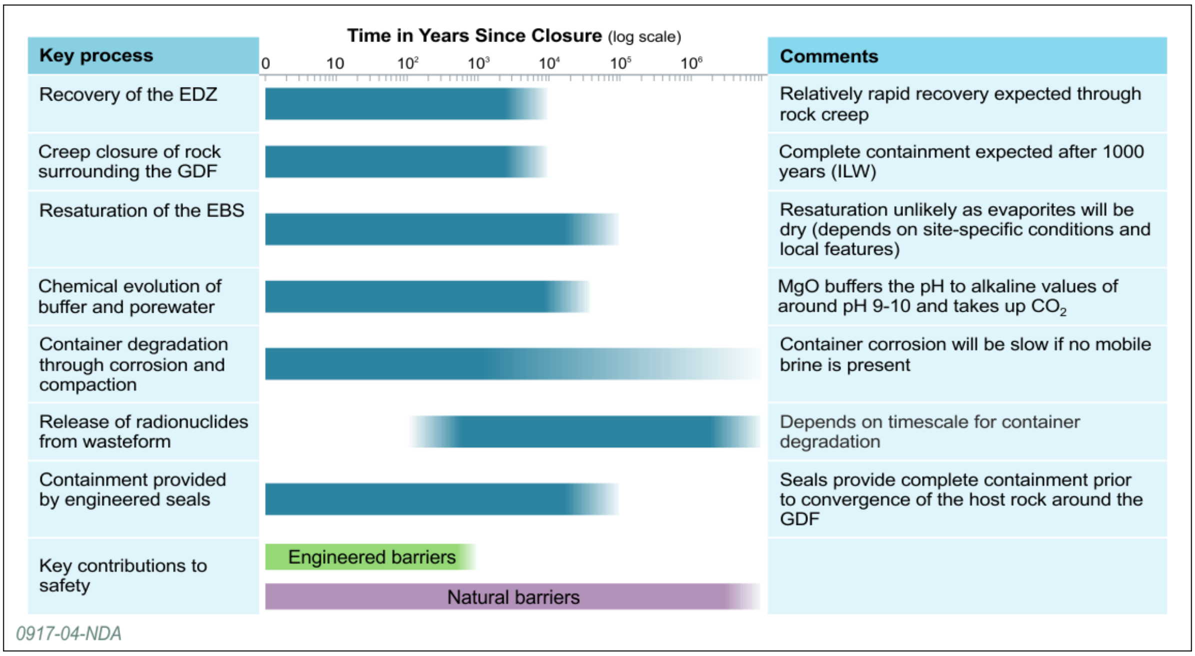
An EDZ in evaporite host rock, and creep, will need to be managed during the operational phase. After closure, creep of the host rock will rapidly fill voids and seal fractures introduced by the disposal system. By the time significant waste package degradation has occurred complete containment will be provided by the host rock.

This section provides a summary of the key steps in the near-field evolution of the illustrative concept example for the disposal of ILW / LLW and the impact this will have on surrounding evaporite host rock.

The behaviour of a disposal system in an evaporite is dominated by the coupled processes of deformation of the rock surrounding the excavation, fluid movement (if any), thermal effects and wasteform/waste package degradation. Each of these processes can be described independently, but they are strongly inter-dependent; the extent to which each process occurs will be affected by the others [340].

The approximate timescales over which key processes dominating the evolution of this illustrative disposal concept are expected to occur are illustrated in Figure 42. Many of these near-field processes occur simultaneously and are most pronounced during the early post-closure period.

Figure 42 Timeframes over which key near-field processes are expected to occur for the illustrative ILW / LLW disposal concept in a halite host rock. T=0 is set as the time at which the GDF is closed.



Evolution during construction and operation of the GDF

Salt creep will begin immediately following excavation, driven by the presence of a differential stress due to the creation of void spaces. Scraping of vault walls, ceilings and floors will be necessary during construction and emplacement to keep facilities open until operations are complete. During construction and operation, any heat generated in the GDF will be dissipated by ventilation and by heat transfer through the surrounding host rock. Oxidising conditions will predominate in the near field during this phase, but these will quickly revert to reducing conditions once the GDF is closed.

Ventilation of the GDF during construction and operation will help to maintain the state of the EBS and the exposed host rock prior to sealing by removing moisture.

Early post-closure evolution

Rock creep around the GDF will continue; the geological barrier will provide increased containment in its own right as time progresses.

Early on, the impermeable components of the shaft seals (such as possibly concrete, clay and asphalt) will be important to prevent inflow of water from the surface to the GDF, as well as to prevent rapid radionuclide transport to the accessible environment. Compaction and creep of crushed salt components of tunnel and shaft seals due to rock creep will render their permeability similar to that of the host rock within approximately 200 years. This will prevent water circulation in the disposal region and to the accessible environment. Cooling of the host rock in the vicinity of cementitious seal components may cause localised cracking of the halite due to thermal contraction. However, this is unlikely to be spatially extensive, and over time, will recover through rock creep.

The rapid recovery of the EDZ expected through rock creep will enable fractures to seal. The recovery of the EDZ around the disposal shaft will be aided by the resistance of rigid components of the shaft-sealing system. The EDZ around the shaft is therefore not expected to provide a continuous pathway for fluid flow. Later, the rigid resistance of compacted backfill in the disposal tunnels will also encourage sealing of any remaining fractures surrounding the GDF.

Any resaturation of the GDF constructed in such a host rock will be a very long-term process. Gas pressurisation due to waste package degradation may provide pathways for any fluid present to move outward from the excavated region, since pressurisation may cause fracturing of more brittle host-rock layers. However, in such a geological environment, gas generation will be limited by the availability of water.

Late post-closure evolution

After several thousands of years, the engineered barriers are likely to be significantly degraded. Multiple breached waste packages are expected due to compaction, enhanced by rock creep, and as a result of various chemical degradation processes. However, by the time significant waste package degradation has occurred and other engineered barriers have also failed, complete containment of the waste in the GDF will be provided by the host rock. An important requirement for long-term safety at this point is to have ensured, through the site selection and disposal system design processes, that there is no mechanism for preferential transport of fluid (and radionuclides) to the surface. If these design and siting requirements are satisfied, then no radionuclide release is expected for a normal (undisturbed) disposal scenario.

7 Developing understanding of the geosphere

An understanding of the geosphere at the selected site for the GDF will be essential to inform the design of the facility and the development of the safety case. This section describes the approach to building that understanding. It describes the way in which we are planning to characterise a site and the way in which modelling will be used to interpret site information and to support the safety case.

Examples are provided which are drawn from a broader international perspective to illustrate where these approaches have been used in different host rock environments.

7.1 Site characterisation

The techniques used for site investigation and data acquisition will be dependent on the potential disposal concept(s) relevant at a site under investigation, and the geology of the site itself.

Site characterisation is an essential part of the process of developing the GDF and has been undertaken in many countries. The specific techniques used for site investigation, and the design of a programme for data acquisition, will be dependent on the potential disposal concept(s) relevant at a site under investigation, and the geology of the site itself. Our approach is described more fully in our Site Characterisation Status Report [410], which is focussed on providing extensive detail as an input to the siting process; key messages of significance to the development of the generic DSSC are however presented in this Section. A clear understanding of the information requirements of the various users of this geoscientific understanding, such as the ESC and the engineering design, is being developed. Preliminary studies to define these information requirements have led us to conclude that they are most appropriately defined in relation to various discipline-based Site Descriptive Models (SDMs); reports on the following discipline-based SDMs have been produced: geology [411]; hydrochemistry [412]; hydrogeology [413, 414]; geotechnical [415]; radionuclide transport properties [416]; thermal properties [415]; and biosphere [417].

Our Site Characterisation Status Report [410] also identifies the various issues for site characterisation, discusses the types of information that may need to be obtained and describes potential data acquisition activities.

7.2 Development of Site Descriptive Models

Site descriptive models developed in a site-characterisation programme summarise the current state of knowledge of the site and provide parameters and models to be used in further analysis within safety assessments, repository engineering and environmental impact assessment.

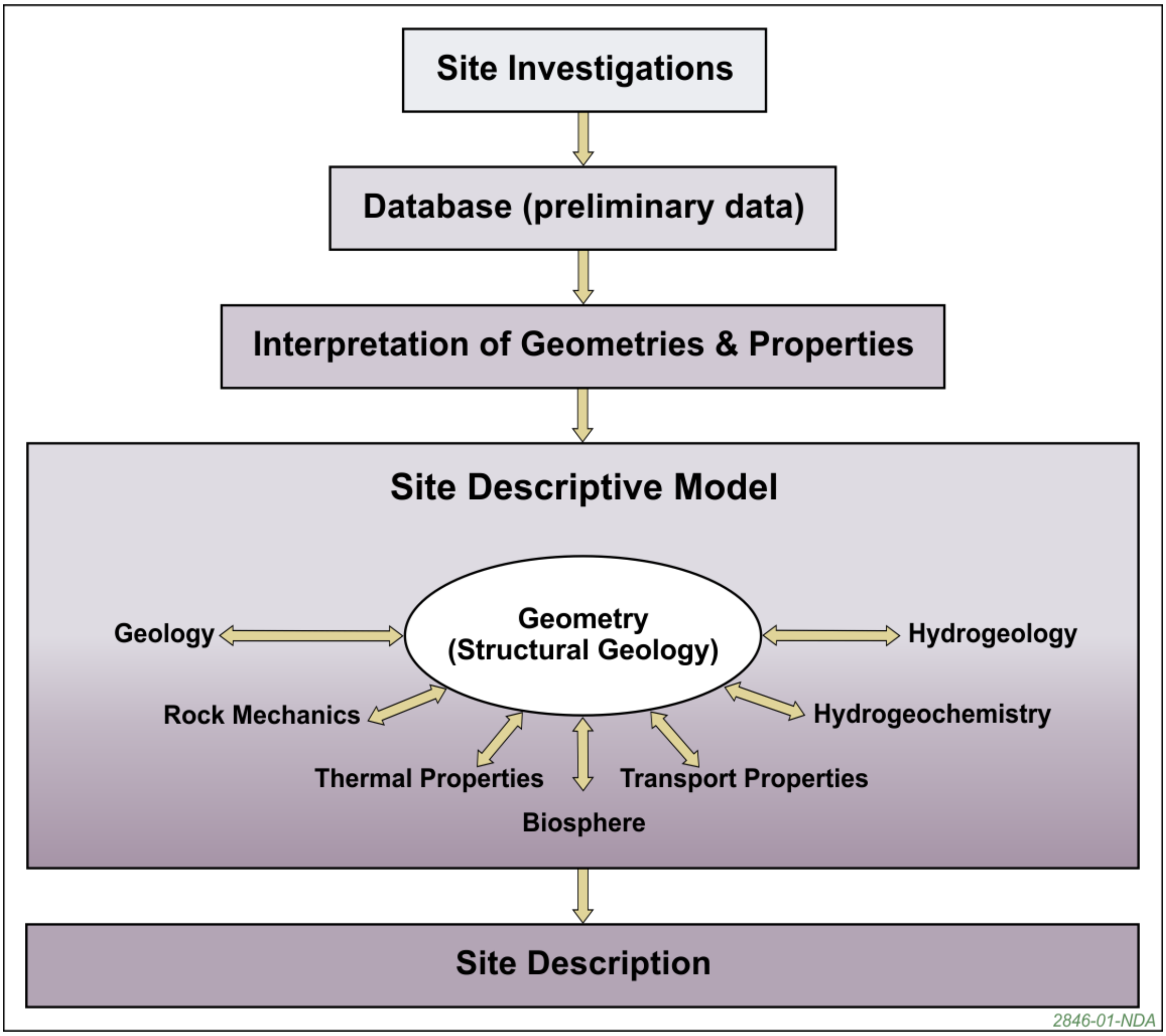
Models are of central importance in many scientific and technical disciplines used by industry and academia. A recent RWM report [418] introduces modelling and explains its potential applications.

Modelling is one of the important tools we use to support aspects of our work to assist the development of the GDF. It is recognised as a powerful tool to test, verify, quantify and predict the outcomes of a range of assumptions and scenarios. In RWM's work, models are developed and applied in a range of scientific and technical discipline areas as diverse as: models to quantify doses to non-human biota, to understand the nature of groundwater flow or to evaluate the consequences of gas generation from waste. Reference [418] provides a technical framework to ensure that RWM has confidence in developing and using these models to support scientific, technical and management decisions.

'Site Descriptive Model' (SDM), as considered in [418], is a term developed by SKB [419, 420]; an SDM is an integrated description of the site and its regional setting, covering the current state of the geosphere and the biosphere as well as ongoing natural processes of importance for long-term safety. The SDM summarises the current state of knowledge of the site, and provides parameters and models to be used in further analysis within safety assessments, repository engineering and environmental impact assessment.

A series of SDMs has been produced as part of SKB's site characterisation process. Each addresses an aspect of the site and its setting. Descriptions of the future development of the seven discipline-specific models are presented in the following sub-sections. Figure 43 outlines the information flow relating to SDMs.

Figure 43 **Site Descriptive Models.** Primary data from site investigations are assembled in a database. The data are interpreted and presented in a site descriptive model, which consists of a description of the geometry of the different units in the model and their corresponding properties. The "site description" then consists of the site descriptive model together with the databases on which the model is based. Modified from [421].



7.2.1 Geology site descriptive model

The geological model describes the geology of the area in sufficient detail in terms of its stratigraphy, structure and lithology to provide a framework for the development of the other site descriptive models.

The purpose of the descriptive geological model is to describe the geology of the area in sufficient detail in terms of its stratigraphy, structure and lithology to provide a framework for the development of the other site descriptive models. The demonstration of geological understanding is also a critical aspect of being able to demonstrate a thorough geoscientific understanding of the site. The development of the descriptive geological model is largely independent of the other descriptive models, but will provide input into all of the other site descriptive models except for the hydrochemistry model.

The ongoing development of the descriptive geological model will take account of developments within the other descriptive models, which may provide additional insights into the identification of geological features and boundaries. The information required to compile the descriptive geological model includes the topography of the region, the geomorphology of the site, the nature and distribution of superficial deposits, sedimentary rock cover, host rock, structural geological features, spatial heterogeneity of the geological units, post-glacial faulting, geological evolution of the area, geochemical and isotopic compositions, tectonic stability of the site and the nature of mineral exploitation at the site.

7.2.2 Hydrogeology site descriptive model

It is necessary to develop an understanding of the hydrogeology at a site in sufficient detail to judge the suitability of the site and to meet the needs of safety assessments and engineering design. The descriptive model will provide an understanding of the evolution of groundwater flow through the various geological formations and hydrogeological units.

The hydrogeology of the site is distinct from the geology of the site in so far as it examines the occurrence of groundwater in the rocks of the site, the movement of the groundwater, the local and regional controls governing this movement and the driving forces that are operating. It also embraces the transport of dissolved materials or particulates within the groundwater and may extend to the consideration of the migration of gases, if appropriate to the site conditions. Information on the hydrogeology of the site is required in order to:

- compile a hydrogeological description on a regional to local scale that is sufficiently detailed for judging the suitability of the site and to meet the needs of safety assessments and engineering design
- provide an understanding of the evolution of groundwater flow through the various geological formations and hydrogeological units
- establish baseline conditions with respect to groundwater pressures, including definition of any spatial and temporal changes, before the groundwater system is significantly perturbed by underground excavations at the site.

The development of the descriptive hydrogeological model relies on a number of inputs from other descriptive models, including the geology, thermal, hydrochemistry and geotechnical models.

A host of modelling methods are expected to be used to support the site-descriptive model; as demonstrated in a recent review [411] of the hydrogeological modelling methods and tools used to support overseas waste management organisations, including the Finnish, Swedish, UK, US, Canadian, Swiss and French programmes. Depending on the geology of the candidate site, the UK programme may require extensive modelling work on both surface/near-surface water and deeper groundwater.

Surface hydrogeology modelling has been extensively developed in the context of fractured crystalline bedrock potentially connected with the subsurface (such as in Sweden and Finland) due to the need to characterise recharge into fractures. On the other hand, hydrogeological modelling in the context of sedimentary basins (such as in the Canadian and French programmes) and evaporite sites (WIPP in the USA) does not necessarily require surface water modelling efforts due to the low permeabilities of the host rock, but typically requires the consideration of multiphase flows (water and gas) and/or thermo-mechanical coupling.

A comparison of the modelling methods for different types of host rock used by overseas waste management programmes found that regardless of the programme, groundwater modelling always consisted of an equivalent porous medium (EPM) modelling approach [411], which frequently used finite element codes. The main differences between the programmes lay in the way that the EPM was built or in the site-specific processes that have to be considered.

The review in [411] determined that, in all programmes, the conceptualisation of the host rock and its surroundings into hydrogeological units has been based on hydraulic testing results at the field scale. The main differences between the overseas programmes' results from the existence (or not) of fractures through the host rock which can be modelled deterministically (hydraulic conductors) or stochastically (discrete fracture network) using information about orientation, aperture, frequency and transmissivity deduced from complementary techniques.

The models use both widely available software and commercial software for databases, data visualisation and geological modelling. Site-specific factors have an influence on the choice of software for building the hydrogeological models. Lower strength sedimentary rock programmes have often used generic geological models such as GoCAD; higher strength rock programmes have often involved specialised tools such as CONNECTFLOW [422].

7.2.3 Hydrochemistry site descriptive model

The hydrochemistry model describes the chemistry of the groundwater system, and the chemical environment in which the disposal facility will be located.

The purpose of the descriptive hydrochemistry model is to describe the chemistry of the groundwater system, and specifically the chemical environment in which the disposal facility will be located. It is a necessary input to the ESC and to the design of the facility to be developed. Of particular importance is the demonstration that groundwater flow in the host formation is relatively stagnant and is not well-connected with the more active near-surface groundwater-flow regime. The acquisition of hydrochemical data contributes towards the development of a number of site descriptive models, including the groundwater and geotechnical models. Hydrochemical information will be integrated with a number of other site characterisation data and generic process models for the EBS, geosphere and biosphere, including:

- EBS performance model
    - modelling groundwater compositions in the EBS and up-gradient of the GDF location
- groundwater flow model
    - definition of groundwater bodies

    - developing a conceptual understanding of groundwater flow, contaminant transport and boundary conditions
- geosphere pathways model
    - modelling groundwater compositions at GDF depth
    - modelling hydrochemistry of transmissive faults and other flow paths down-gradient of the GDF location
    - developing a geochemical description of radionuclide transport pathways, including fracture minerals and the adjacent rock matrix
- biosphere and geosphere-biosphere interface zone (GBIZ) models
    - modelling the hydrochemistry of shallow groundwaters, soil waters and surface waters
    - developing understanding of the geochemical compositions of soils
    - providing understanding of the baseline geochemical conditions of the surface environment.

Specifically, the hydrochemical modelling programme [412] will be used to:

- evaluate possible impacts of sampling on groundwater compositions
- derive calculated parameters such as partial pressures of carbon dioxide and mineral saturation indices from hydrochemical data
- assist in the interpretation of hydrochemical data from water samples with reference to the known hydrochemistry of the groundwater environment
- estimate key parameters that may not be measurable in situ
- develop models that describe how the hydrochemical environment has evolved during the recent geological past.

The two main modelling tasks [412] will be the coupling of solute transport and non-reactive hydrochemical evolution with groundwater flow and simulations of reactive mass transfers and long-term buffering of hydrochemical conditions by water-rock interactions.

7.2.4 Geotechnical site descriptive model

The geotechnical model describes the geomechanical properties of the host rock formation and the cover sequence for engineering design purposes.

The purpose of the descriptive geotechnical model is to describe the geomechanical properties of:

- the host rock formation for engineering design of the underground works
- the cover sequence for design of accesses to the host rock formation; and the near-surface soils and rocks to facilitate the design of surface infrastructure (such as foundation design).

The descriptive geotechnical model will also provide information to support the overall safety assessment through consideration of glacial unloading, thermal loading, the effect of rock stresses on hydrogeological evolution, the assessment of any excavation damaged zone(s), the potential for rock spalling, and the significance of construction-induced water-flow pathways. The development of the descriptive geotechnical model relies on a number of inputs from all other descriptive models except the transport properties model:

- for geotechnical site understanding, a strong link to the geological model which provides the geometric framework for expanding point values into volumes is important
- understanding the rock stress regime at a site may be complicated if the site has a complex deformation history
- statistical and geostatistical approaches are useful for determining the geotechnical and thermal properties at a site and understanding the scale effects
- in lower-strength sedimentary rocks, interpretation and modelling are likely to focus on the development of models that describe rock behaviour by using micro-mechanical models, short and medium-term deformation models and long-term deformation models (creep) as well as continuous rock mechanics models with curved failure surfaces
- high-resolution 3-D seismic reflection surveys can be used to characterise and interpret geotechnical parameters, especially in a homogeneous formation
- hydro-mechanical and thermo-mechanical couplings will be taken into account in the interpretation of data from lower-strength sedimentary rocks
- laboratory analysis, constitutive model formulation, and numerical modelling are likely to be required in the development of thermal/structural codes to understand the creep deformation of evaporites. The models are likely to evolve significantly as information from underground excavations becomes available.

7.2.5 Radionuclide transport properties site descriptive model

Important radionuclide transport processes include advection and dispersion, diffusion, transport by colloids and transport in gaseous form. Radionuclide retardation and immobilisation processes include sorption, complexation, precipitation, molecular filtration and ion exclusion, rock-matrix diffusion, microbial activity and gas-entry pressure effects.

The main processes relevant to radionuclide transport from the GDF are well known and understood. These processes can be grouped into two categories:

Radionuclide transport processes

- advection and hydrodynamic dispersion. In some higher strength rocks, groundwater flow is predominantly through fractures. For such rocks, advection and hydrodynamic dispersion take place in the fractures
- diffusion - in some lower strength sedimentary rocks diffusion, rather than advection, is the dominant transport process
- transport by colloids and microbes
- transport in gaseous form.

Processes relevant to radionuclide retardation and immobilisation

- Sorption, including ion-exchange processes
- complexation
- precipitation/co-precipitation
- molecular filtration and ion exclusion (which would act to reduce retardation)
- Rock-matrix diffusion. In rocks in which groundwater flows predominantly through fractures, radionuclides migrating in the flowing groundwater can also diffuse

between this moving groundwater and relatively immobile water in the rock matrix between the fractures

- microbial activity
- capillary barrier effects (gas entry pressure effects).

Precipitation/co-precipitation of major ionic species on fracture surfaces could reduce the number of available sorption sites.

The parameters required to characterise processes typically considered in a safety case are:

- flow-related parameters (the flow field, groundwater travel time and, in fractured rocks, the transport resistance along flow paths)
- accessible flowing porosity for rocks in which transport is advection dominated. Ion exclusion effects need to be considered
- intrinsic diffusion coefficients for the radionuclides of interest for very low permeability rocks in which transport is diffusion dominated
- dispersion parameters for rocks in which transport is advection dominated. For rocks in which the flow is predominantly through the rock matrix, these will usually be based on empirical correlations with distance. For rocks in which the flow is predominantly through fractures, and discrete fracture network models are used, the dispersion parameters will usually be implicitly related to parameters of the fracture network. If continuum porous medium models are used for such rocks the dispersion parameters may again be based on empirical correlations
- sorption parameters for the radionuclides of interest. It is expected that sorption will be represented in terms of sorption distribution coefficients (K_d) using a linear equilibrium reversible sorption model
- rock-matrix diffusion parameters for those rocks in which groundwater flow is predominantly through fractures. The relevant parameters are those which characterise the geometry of the rock matrix (which will depend on the parameters of the fracture network), the intrinsic diffusion coefficients and accessible porosities in the rock matrix for radionuclides of interest. Ion-exclusion effects need to be considered
- gas transport parameters. These include the two-phase flow characteristic functions of the capillary pressure (in particular the gas-entry pressure) and the relative permeability.

The tools used in interpretation and modelling of radionuclide transport in groundwater in the geosphere vary from simple one-dimensional numerical (or mathematical) models, to physically based three-dimensional numerical models. Simplified transport models, using for example, networks of one-dimensional models of transport along paths may be used in performance assessment calculations for rocks in which transport is advection dominated in order to reduce the computational resources required. This is particularly important for probabilistic calculations, which require calculations for many realisations in order to have good statistics. Detailed three-dimensional physically-based numerical models may be used:

- for rocks in which transport is diffusion dominated
- to inform the development of simplified performance assessment models
- to check the simplified performance assessment models
- to analyse the results of field transport experiments

- to model the transport of natural tracers, which can be used to build confidence in the models, by showing that they can acceptably predict the transport of natural tracers.

Other tools such as thermodynamic codes, databases, visualisation tools and tools for linking codes may also play important roles. Two-phase (or multi-phase) flow codes are used for modelling gas migration from the GDF.

One very important point to appreciate is that the parameters used in assessment models do not correspond directly to the quantities measured in experiments. This is because the parameters of the assessment models represent the overall behaviour of large volumes of rock, whereas the measurements characterise much smaller volumes. An assessment parameter therefore represents an average (not necessarily arithmetic) of the varying small-scale property. Also, a measurement addresses particular geochemical conditions, whereas in assessments, ranges of geochemical conditions are considered.

The parameters used in quantitative assessment models will be based on a combination of values measured in site-specific experiments and generic literature values. Further, values for some radionuclides may be based on (site-specific or generic) values for the radionuclides in question. However, for some radionuclides, the values may have to be based on values measured for analogue elements. Many radionuclides and many different rocks/features, and ranges of geochemical conditions (such as pH and Eh) are likely to be considered. It would not be practicable, nor is it likely to be necessary, to carry out site-specific measurements for all combinations of radionuclides, rocks/features and geochemical conditions. Therefore, a strategy is proposed that matches the level of investigation to the importance of a parameter in the performance assessment, and in particular to the identified safety functions. It should be recognised that the understanding of the importance of the parameters will develop over time, and so there will need to be continuing interactions between site characterisation and performance assessment.

7.2.6 Thermal site descriptive model

Information on the thermal properties of a site is required as inputs to hydrogeological modelling and to thermal modelling which may be used to inform design of the facility.

Thermal modelling is an important consideration for a geological disposal facility where there will be a significant proportion of heat-generating waste within the inventory. The presence of heat-generating wastes will have an impact on the positioning of disposal modules for the different types of waste. When rock is heated by heat-generating waste the rock expands, thus creating additional stresses which may affect the mechanical and hydrogeological properties of the rock mass. The thermal properties of the rock mass could also affect the spacing between individual deposition modules and could, thus, have a significant effect on the total underground footprint of a geological disposal facility.

Information on the thermal properties of a site is required for a variety of purposes, including:

- input to hydrogeological modelling
- assessment of temperatures in underground excavations in relation to the engineering design of the works, particularly related to ventilation required to control temperatures during construction and operation of the facility
- as an input to thermal modelling of the near-field geological disposal facility conditions, which may be used to inform design of the facility.

7.2.7 Biosphere site descriptive model

Information and understanding of the characteristics of the biosphere are required for both the operational safety assessment and post-closure safety assessment at a site.

The biosphere can be considered as comprising the region of the site from the Earth's surface, extending to a depth which either provides groundwater for drinking purposes or provides base-flow to rivers. As such, the biosphere represents the portion of the site where humans and most organisms live (the receptors for any contamination). The depth to the biosphere / geosphere interface will be dependent upon the local site conditions and may extend to depths of several hundred metres in areas underlain by significant groundwater resources. Generally speaking, the biosphere is more dynamic than the geosphere and its evolution through time can significantly affect the potential impacts of a geological disposal facility (for example, due to climate change, glaciations, etc.).

Information on the biosphere is required to:

- demonstrate scientific understanding of the characteristics of a site
- provide part of the basis for the operational safety assessment of a geological disposal facility at a particular site, and
- provide part of the basis for a Post-closure Safety Assessment (PCSA) of the geological disposal facility at a particular site (see [423] for a generic example).

There will be considerable overlap in the information required to support the development of the descriptive biosphere model, required to support the development of an ESC, and that required for the purposes of the Environmental Impact Assessment (EIA), to accompany planning permissions for both the site investigation activities and for the geological disposal facility.

The descriptive biosphere model is prepared on the basis of interpretation of data collected from a wide range of sources, including inputs from the geology, hydrogeology and hydrochemistry models.

7.2.8 Data requirements for site descriptive models

Most data will need to be interpreted to derive parameters or understanding suitable for use in the site descriptive models. Appropriate consideration of uncertainty will be important.

The types of data required as inputs to each SDM are discussed in the Site Characterisation Status Report [410], and are therefore not reproduced here. Some of these data can be used directly in the SDM. Most data will need to be interpreted to derive parameters or understanding suitable for use in the SDMs. The process by which this will occur is summarised below:

- *data acquisition* – to obtain measurements and to collect data using a range of measurement techniques and surveys
- *data processing* – to transform measurement data into information that is meaningful in terms of the properties of the site
- *interpretation* – to understand the significance of that information in terms of the individual aspects of the site (for example, groundwater flow, geology, environmental processes, etc.)
- *integration* – to develop a consistent understanding of the site as a whole, including all the individual aspects

- *communication* – to communicate the understanding obtained to others (such as those involved in the development of the environmental safety case, engineering design or Environmental Impact Assessment, and key stakeholders) and to obtain feedback that could influence the ongoing process of site characterisation.

As site characterisation proceeds, the SDMs will be developed and refined. Alternative conceptualisations of aspects of the site may be appropriate, and it will be important that the SDMs reflect this.

Ultimately, the different discipline-based SDMs must be brought together to provide an overall geoscientific understanding of the site. It is expected that the overall understanding will comprise:

- measurements in adequate detail to show the site as it is now ('initial state')
- interpretative models that integrate measurements into an adequate understanding of relevant processes
- a model that forecasts the long-term evolution of the site
- a model that forecasts the effect on the geosphere behaviour of constructing and operating the GDF
- realistic estimations of uncertainties in all measurements and models and identification of alternative conceptual and interpretative models.

In addition, although collection of more data will reduce uncertainty in parameter values (for example, the permeability of the rock), some uncertainty will inevitably remain. Estimation and treatment of uncertainty are important issues both for the SDM and for the subsequent assessment modelling. There are several types of uncertainty that need consideration:

- uncertainties concerning the representation of processes in models and computer codes representing the geological disposal system. This type of uncertainty is often called 'conceptual model' uncertainty
- uncertainties associated with the values of the parameters that are used in the implemented models. These are variously termed 'parameter' or 'data' uncertainties
- uncertainties in future states of the geological disposal system. These are often referred to as 'scenario' or 'system' uncertainties
- uncertainties in future human behaviour.

7.3 International experience in site investigation

Site investigations and safety assessments for geological waste disposal have been carried out in many countries. Subsurface radioactive waste disposal facilities are already in operation in several countries.

There is a large international community making progress on site investigations and safety assessments for geological waste disposal. Subsurface radioactive waste disposal facilities are already in operation in several countries, including Sweden and Finland (at Forsmark and Olkiluoto respectively, for the disposal of LLW and short-lived ILW) and the USA (at WIPP, which is used for disposal of transuranic wastes). Characterisation of these sites was an essential part of the site selection and authorisation process.

We have commissioned a review of these international surface-based site investigations that have been undertaken, or are being planned or implemented. The review [410] included programmes across the United Kingdom, the other countries in Europe and in North America. This was a desk-based exercise, using published information and some discussions with specialists involved in several of the programmes. The programmes considered in this review were:

- UK Nirex - historic investigations at a number of UK locations
- UKAEA - Dounreay Shaft Hydrogeological Investigation Project
- Finland, Posiva
- France, Andra
- Sweden, SKB
- Switzerland, Nagra
- United States, Waste Isolation Pilot Plant (WIPP), US Department of Energy (DOE)
- United States, Yucca Mountain, US DOE
- Canada, Bruce, Ontario Power Generation.

We will continue to work alongside other international geological disposal programmes and will keep a watching brief on other sectors that undertake site characterisation in order to maintain an up to date understanding of site characterisation activities and available techniques.

7.4 Natural analogues

Analogues - natural, archaeological and industrial - can be helpful in demonstrating understanding of aspects of GDF performance and can provide evidence that certain materials can survive for long periods. They can be useful in providing supporting arguments in a safety case.

A consideration of 'natural analogues' plays an important role in GDF-related geosphere studies. The generally accepted definition of this term [424] is "*...an occurrence of materials or processes which resemble those expected in a proposed geological waste repository*". This has subsequently been refined by the addition: "*The essence of a natural analogue is the aspect of testing of models - whether conceptual or mathematical - and not a particular attribute of the system itself*" [425], and by an IAEA (International Atomic Energy Agency) review group [426]. The progressive refinement of the definition reflects a maturation in the understanding and appreciation of natural analogues. In essence, natural analogue studies use information from the closest possible approximations, or direct analogies, of the long-term behaviour of materials and processes found in, or caused by, a repository in order to develop and test models appropriate to performance assessment work.

Analogues, whether natural, archaeological or industrial, can be helpful in demonstrating understanding of aspects of GDF performance and can provide evidence that certain materials can survive for long periods. However, they do not provide conclusive proof that these materials will survive for the required periods in the environments of a particular GDF, as the conditions under which the analogue material has survived may not match those expected to occur or evolve in the GDF. Therefore, analogues should only be used with caution, and can only ever provide supporting arguments in the generic Disposal System Safety Case [427]. Nevertheless, appropriate analogues can be helpful in providing a long-term practical demonstration to support the theoretical and mathematical arguments.

RWM participates in the international Natural Analogue Working Group [428]. We haves also recently participated in the Cyprus Natural Analogue Project (CNAP), see [429, 430, 431, 432] for further information.

To provide a reference source of safety-relevant examples from natural systems that could be used to support the ESC, RWM has produced a catalogue of natural analogues for radioactive waste disposal [433]. Its scope includes all aspects of disposal relevant to the UK situation; a range of waste types and potential GDF host rocks are considered and examples are grouped into four main sections - the engineered barrier system, natural barrier system, radionuclide migration in natural systems, and natural analogues and the safety case. Recent other work RWM has published in relation to analogue studies is reported in references [429, 430, 431, 432, 434, 435].

7.5 Modelling of groundwater flow and transport

Groundwater flow models will be needed at a number of length scales in support of both site descriptive models and safety assessments. A regional model is likely to be a continuum porous medium model. Local scale models can be of various types; they may also be (more detailed) continuum porous medium models, or discrete fracture network models.

Groundwater flow models are likely to be required at a number of length scales in support of both SDMs and safety assessments. The most common will be regional models and local-scale models. A regional model might extend over distances of tens or hundreds of kilometres, whereas a local model (which 'nests' within the regional model) may extend to distances of, for example, a few tens of kilometres. Boundary conditions for the regional model will be determined from the relevant physical processes (such as the positions of regional groundwater divides and related catchments), whereas the boundary conditions for the local models will generally be obtained from the results of the calculations for the regional model.

A regional model is likely to be a continuum porous medium (CPM) model. For sedimentary basin settings, it might be appropriate to use a proprietary modelling code. In such models, groundwater flow on a representative scale is represented by average hydrogeological properties. A CPM representation will be used both for rocks in which the groundwater flows through pores in the rock matrix and for those in which it flows through fractures. The model is likely to include explicit representations of larger features (such as regional faults), although not of smaller features such as individual fractures. Local-scale models generally provide a more detailed representation of the smaller area. This is due both to scale effects (in any model there is generally a practical upper limit on the number of 'elements' into which the area is sub-divided) and because more site characterisation data are generally available in the local area of interest. Local scale models can be of various types; they may be CPM models, albeit with a more detailed representation. They may be discrete fracture network (DFN) models, which explicitly represent the network of intersecting fractures in higher strength rocks through which groundwater flows. Typically, such local-scale models may represent flow as occurring through a network of connected pipes, or channels.

There have been many detailed studies of groundwater flow and transport modelling in a number of different geological settings. Some examples of UK work are given in [436] and [437]; see also [11], Tasks 390 and 391.

7.6 International experience of modelling flow and transport in the illustrative geological settings

There is a capability (in the UK and internationally) to model groundwater flow and transport in all of the illustrative geological settings being considered in the UK.

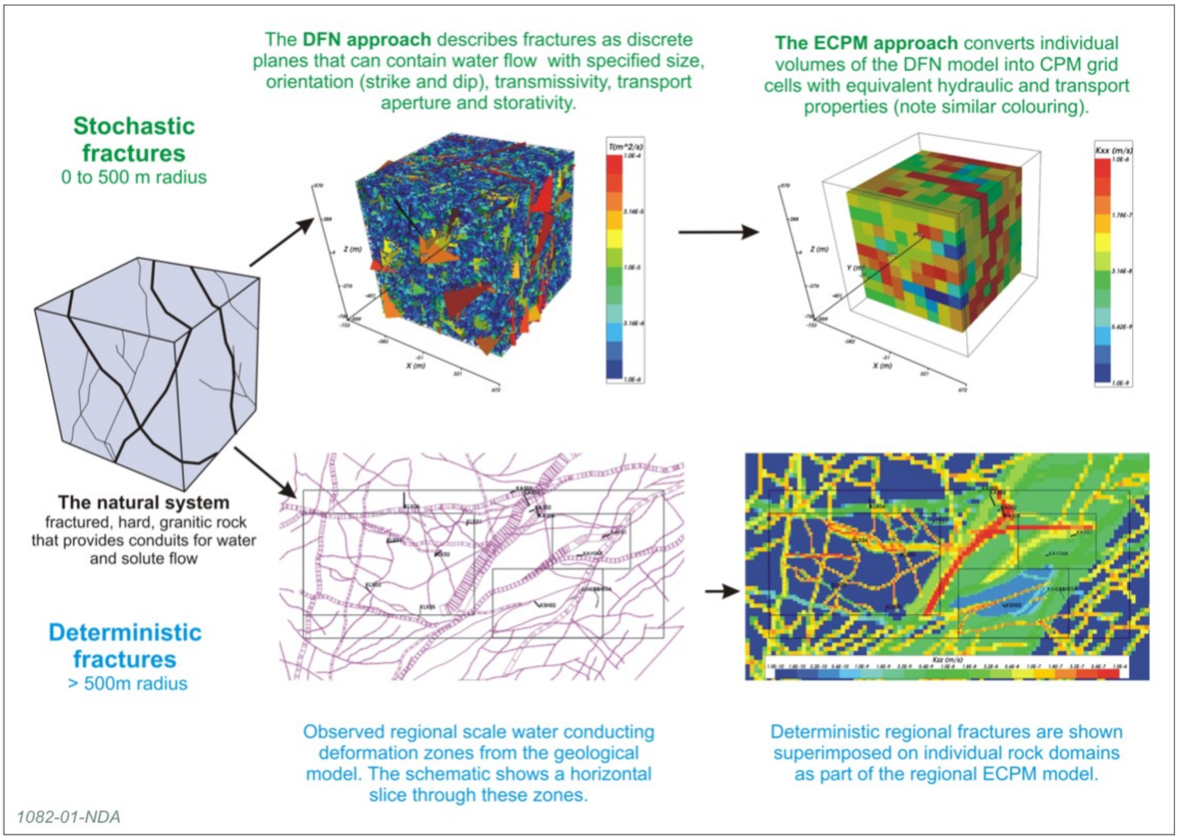
This section provides examples of how numerical modelling has been applied to describe a range of processes in the three illustrative geological settings described earlier in this report. These examples have been provided to demonstrate that there is a capability to model groundwater flow and transport in all the illustrative geological settings being considered in the UK. This gives confidence that appropriate models can be developed once sites have been selected. The first example is taken from the Swedish programme and illustrates the use of palaeohydrogeological data and modelling to build confidence in models used for safety assessments. The second example illustrates an initial scoping assessment by Andra of the extent of the EDZ in a lower strength sedimentary rock. The third example describes modelling performed in the operational phase of WIPP.

7.6.1 Higher strength rocks: SKB example [14]

SKB has carried out site investigations in two different candidate areas in Sweden, Forsmark and Laxemar, with the objective of describing the *in-situ* conditions for a deep rock repository for spent nuclear fuel. This example illustrates a modelling study performed as part of these preparatory investigations on the site in the Simpevarp (Laxemar) area, located on the east coast of southern Sweden. The objective was to describe groundwater flow and transport of natural groundwater tracers in the fractured rock so as to simulate the past and present day natural system. This is an illustration of some of the progress towards full integration of hydrochemical information within hydrogeological models.

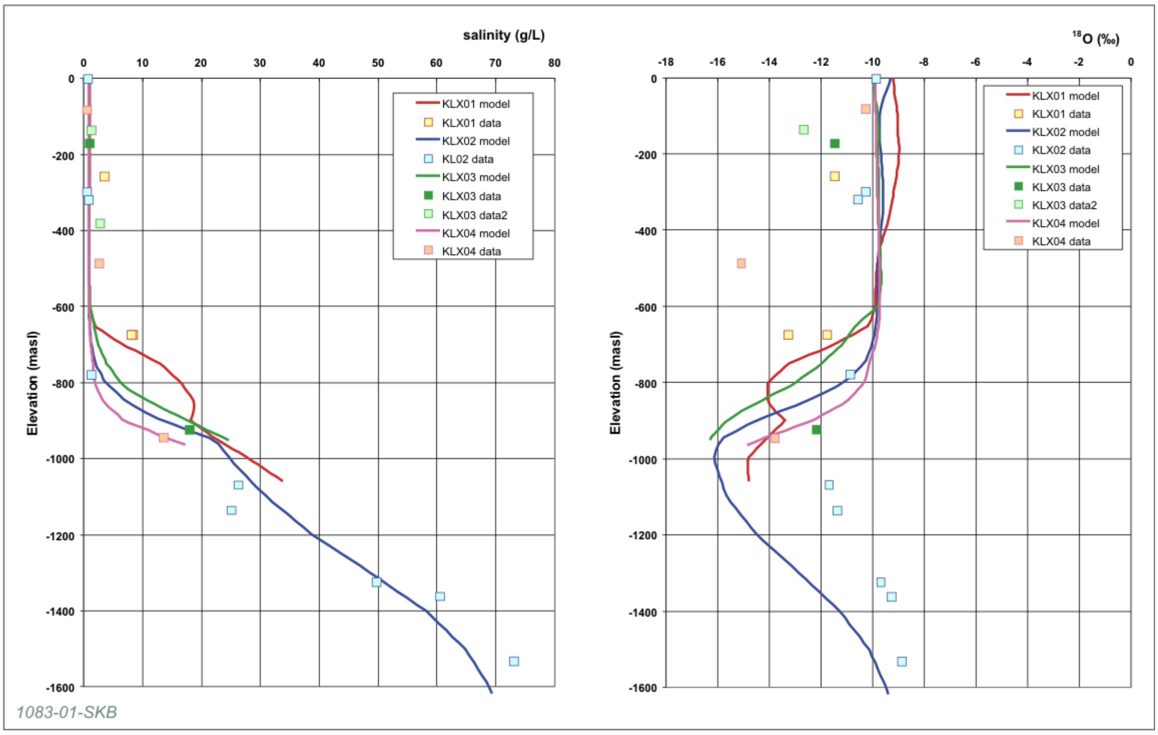
A transient coupled regional model of groundwater flow and solute transport was developed, which allowed the use of hydrochemical data to calibrate the model input parameters. The three-dimensional hydrogeological model was developed from a stochastic description of the water-conducting fractures and effective properties were upscaled to parameterise a regional scale model. The three-dimensional model was used to integrate the water conducting features, which give rise to the descriptions of spatial heterogeneity (illustrated in Figure 44), density-driven flow, rock matrix diffusion and transport and mixing of different water types. Note that both the DFN and CPM approaches are based on the same underlying parameters of fracture frequency, orientation, length, transmissivity and transport aperture.

Figure 44 The alternative modelling approaches to describing groundwater flow, using DFN and CPM models (ECPM refers to "Equivalent Continuous Porous Medium")



The model was used to simulate the evolution of groundwater chemistry over the post-glaciation time period between 8000 BC and 2000 AD in order to calibrate the hydrogeological properties of the groundwater system. Figure 45 presents groundwater salinity data (on the left hand side) and model simulations for the base case hydrogeological model at the present day. In this figure, the best available groundwater salinity measurements from deep cored boreholes (KLX01 to KLX04) are shown as squares. Model simulations of groundwater salinity for each of the four boreholes are shown as solid lines. In Figure 45, corresponding data and model simulations for the relative oxygen isotope ratio, $\delta^{18}O$, in the groundwater are shown on the right hand side. This figure shows how the integrated hydrogeological and hydrochemical model captures the trends in the overall characteristics of the hydrochemistry at the site. This builds confidence that the representation of hydrogeological aspects such as the groundwater circulation pattern (the depth of penetration of recharging groundwater into the rock and the locations of recharge and discharge), and the groundwater flux through the higher strength rock, is realistic.

Figure 45 Comparison of salinity and relative oxygen isotope ratio, δ18O, in four boreholes at the Simpevarp site in Sweden.



7.6.2 Lower strength sedimentary rocks: Andra example [14]

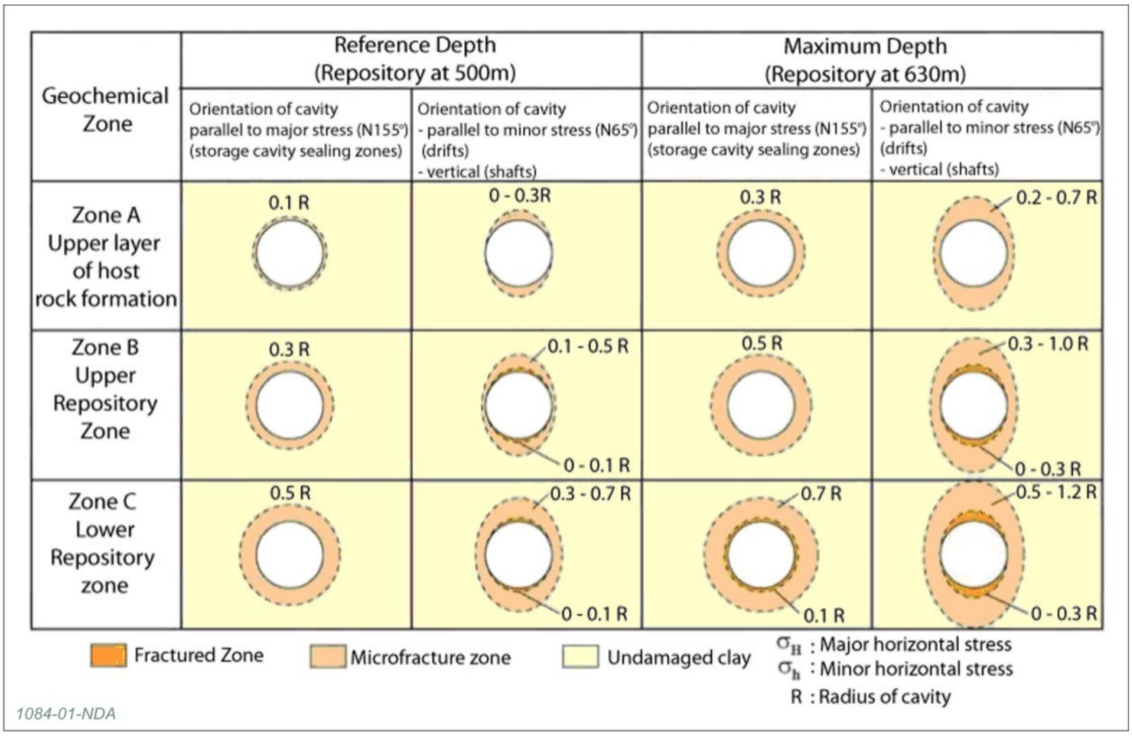
As indicated in Section 6.3, excavating an underground structure will potentially create an EDZ in the vicinity of the walls of the excavation. International collaborative research, involving waste management organisations such as Nagra (Switzerland) and Andra (France), has been performed to investigate EDZ formation at the Mont Terri underground laboratory, which is located in Opalinus Clay. Work at this facility has identified two distinctive damage zones caused by excavation. A fractured zone in the vicinity of the engineered structure is produced if the rupture threshold, corresponding to the maximum mechanical strength of the rock, is exceeded. This is characterised by the appearance of more connected fractures parallel with the axis of the drift, which may increase the hydraulic conductivity of the rock locally, as shown in Figure 46 (from [438]). In addition, a microfissured zone is produced when the fissuring threshold is exceeded in the vicinity of the engineered structure. Mechanical relaxation induced by the excavation causes deformations that manifest themselves as poorly-connected microfissures. The low connectivity of these features limits the increase in hydraulic conductivity. The fractures and cracks of the fractured and microfissured zones are preferentially oriented parallel with the axis of the structures.

In 2005, Andra presented its initial analysis of the modelling of the EDZ [113]. The modelling assumed that:

- the mechanical properties could be assumed from saturated samples with some consideration of the uncertainty in these data
- there would be no structural support (a circular cross-section for the engineered structure was assumed)
- a relatively simple elasto-plastic law of deformation was applicable
- there was anisotropy in the horizontal and vertical stress.

The hypotheses of minimum mechanical properties and marked anisotropy of stresses adopted for the models tend towards a maximum estimation of the extent of the initial EDZ. Based on the depth of the excavation and its orientation, the extent of the fractured zone is thus assessed at 0 to 0.3 times the radius of the engineered structure and that of the microfissured zone at 0.3 to 1.2 times the radius of the engineered structure. The extent of the reversible disturbances (stresses, deformations) is around three times the radius of the engineered structure.

Figure 46 Numerical modelling assessments of geometries and extensions of the initial EDZ in the Callovo-Oxfordian argillites for the various repository engineered structures [438]



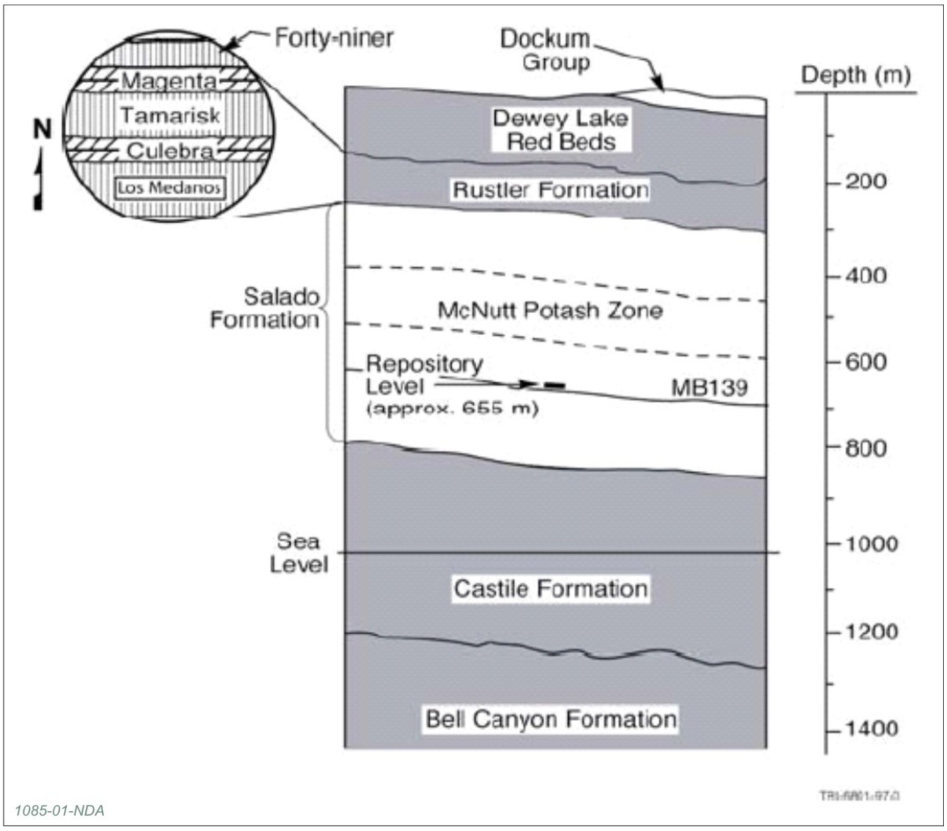
7.6.3 Evaporite: WIPP example

The Culebra Dolomite Member of the Rustler Formation, as shown in Figure 47, is the most permeable fully saturated unit above the WIPP repository horizon and is the most likely groundwater pathway for contaminants released from the repository by potential inadvertent human intrusion. Consequently, the Culebra is the focus of groundwater monitoring at WIPP.

Ongoing monitoring has shown that the groundwater pressure in the Culebra Formation is rising and responds to discrete, present-day events. This is an apparent contradiction of the original 1996 conceptual model, which envisaged steady-state or slowly declining heads. The reason for this predicted behaviour in the original conceptual model was that the Culebra Formation was considered to be effectively isolated from rainfall and other surface hydrological processes (‘confined’) by overlying low permeability rocks. Because of these discrepancies, the US regulator for the WIPP site requested that DoE undertake additional studies of the Culebra Formation and develop a revised conceptual model consistent with recent observations. In response, DoE undertook further site characterisation. The main components of the work were drilling more boreholes, carrying out large-scale pumping tests to determine the permeability of the rock, installing an enhanced monitoring system to measure groundwater heads and developing a better conceptual model to describe the reasons for variations in permeability throughout the formation [439].

The new information collected since 2002 has served to confirm many aspects of the original Culebra conceptual model. However, the most significant revision is that strata overlying the Culebra Formation have in some areas lost their effectiveness as confining beds (that is, strata serving to isolate the underlying strata from recharge), allowing groundwater heads in the Culebra Formation to respond to rainfall. Head changes in this area of the Culebra Formation then propagate through the site area where the Culebra Formation remains confined by the overlying strata. This is likely to be the process that causes most of the changes in groundwater levels that have been observed over the past fifteen years. The revised understanding of Culebra hydrology is consistent with the observed groundwater geochemistry.

Figure 47 WIPP stratigraphic column



A new three-dimensional model of groundwater flow in the Culebra Formation was then developed using MODFLOW-2000 [440] in order to confirm that the revised conceptual model, supported by the improved datasets, can quantitatively explain the field observations. In particular, the model was calibrated (using a program called PEST [441]) to ensure that, at the positions of groundwater monitoring boreholes, the modelled values of permeability, groundwater head and transient hydraulic response to pumping matched the field observations [442]. In general, the calibration results obtained were far superior to those obtained previously. Most importantly, this improved groundwater flow model and the improved, more detailed understanding of Culebra hydrology supports the long-standing conclusion that the Culebra Formation provides an effective barrier to radionuclide transport off the WIPP site. It also demonstrates the adequacy of the previous 2-D confined model used to simulate groundwater flow across the WIPP site.

8 Concluding remarks

The science and technology underpinning geological disposal of the materials currently considered in the UK radioactive waste inventory is well established. The knowledge base includes information from laboratory studies, full-scale and small-scale testing, computer models and studies from a variety of engineering disciplines that can be used to support the implementation of geological disposal.

The key message emerging from the analysis presented in this status report is that the current geosphere understanding is fully consistent with international precedence, and is underpinned by appropriate research. Specifically:

1. There are two high-level principles of geological disposal of radioactive waste, namely to isolate the waste from the biosphere and to contain the radionuclides associated with the wastes.
2. The geosphere contributes to isolation by providing a stable location deep underground that protects the GDF from any perturbations to the natural environment that may occur over the timescales of interest. This shields the surface environment from waste-derived irradiation and considerably reduces the risks of both intentional and inadvertent human disturbances and intrusion.
3. The geosphere contributes to containment by delaying the movement of any potential small amounts of long-lived radionuclides that are released from the engineered barrier system. The geosphere can fulfil its containment role in different ways. In many geological settings, and recognising the role of surface topography, it is the slow movement of groundwater and geochemical retardation or immobilisation that ensures long travel times for some radionuclides released from the GDF, thereby facilitating their radioactive decay within the geosphere.
4. A suitable geological environment is fundamental to geological disposal. A site should be geologically stable in order to ensure safety and also be predictable to the extent required for assessing performance. A stable geological environment is one that is not likely to be subject to sudden or rapid detrimental changes over long timescales because of its buffering capacity with respect to internal and external perturbations.
5. The natural processes which may impact on the geosphere in a UK geological setting over the timescale of the next million years or so, which is particularly relevant to geological disposal, are tectonics, uplift or subsidence and erosion, and the impacts of future climate, particularly potential future glaciations. These natural processes and their potential impacts in the three illustrative geological settings are described. From historical knowledge and research, these processes are understood; therefore their impacts can be predicted with confidence.
6. Our geosphere programme involves participation in international projects, our own R&D programme and generic modelling studies.

Information contained in the suite of research status reports has been used to underpin the development of the 2016 generic DSSC. In particular, information from this status report has been used to provide the technical understanding of the processes associated with the long-term performance of the geosphere.

RWM recognises areas that require further development and issues that can only be resolved as the GDF site selection process progresses towards site-specific assessments.

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