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Illustrative Components of the Geological Environment

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1 Introduction

In this chapter we provide an account of the contribution made by the Geosphere, in particular bedrock geological materials (part of the lithosphere), groundwater and hydrochemistry to the development of a GDF. In order to put this in context we provide a brief account of the general requirements of these attributes, particularly in respect of the post closure safety and, to a lesser extent, the construction phase of the GDF. We also provide a brief summary of the international approach to using bedrock geological materials and go on to describe the summary properties from a range of bedrock geological materials (lithologies and formations) in England, Wales and Northern Ireland, illustrated from well-documented examples.

1.1 CONTRIBUTION OF THE GEOLOGICAL ENVIRONMENT TO A GDF

There has been a considerable amount of research undertaken in recent decades into the geological disposal of radioactive waste. The account presented in this section is largely based on the review of Chapman and Hooper (2012). In the ‘multi-barrier’ concept of geological disposal of radioactive waste, the geological environment provides one of the key barriers that, together with engineered structures, provides isolation and containment of the waste material after closure of the site. The engineering properties of the bedrock geological materials also have a control over the design and construction of the GDF. The geological environment is defined by the bedrock lithology and its associated hydrogeological, hydrogeochemical and geomicrobiological attributes. These together control the behaviour of the bedrock system and determine its suitability and performance as a GDF host.

Isolation and containment are both considered to be safety functions of the GDF system and have been described in the following way: isolation of wastes involves safely removing them from direct interaction with people and the environment; containment of radionuclides involves retaining them within the various components of the multi-barrier system until natural radioactive decay has significantly reduced the hazard potential.

The geological environment contributes to one or both of these functions either as the host to the GDF construction itself or as part of the broader volume around it. This includes the function of low permeability ‘cover’ that might provide additional containment. A further key

feature of the geological environment is its excavatability, i.e. the ease with which engineered voids can be constructed and maintained. Both of these are in part related to the rock strength as well as other physical attributes. The contribution of the geological environment to these two safety functions can be considered in terms of the following attributes (cf. International Atomic Energy Authority, 2011; Environment Agency, 2009, Watson et al., 2007, Nirex, 2005, Nirex, 2003):

1. possesses high strength and low permeability that limit or prevent the flow of deep groundwaters through a backfilled and sealed facility;
2. ensures that chemical, mechanical, hydrogeological and microbiological evolution of the deep system is slow and can be forecast with confidence;
3. possesses properties that retard the movement of radionuclides in groundwater; this includes sorption onto mineral surfaces and dispersion;
4. allows the conduction of heat generated by the waste away from the engineered barrier system so as to prevent unacceptable temperature rises;
5. disperses gases produced in the GDF so as to prevent mechanical disruption of the engineered barrier system.

By consensus bedrock geological formations are generally subdivided into three idealised end-member categories (cf. Chapman and Hooper, 2012): ‘hard rocks’ such as intrusive igneous and metamorphic rock (analogous to ‘higher strength rocks’ of NDA, 2010); ‘soft rocks’ such as clay and mudstone (analogous to ‘lower strength sedimentary rocks of NDA, 2010); and ‘evaporite’. These categories are described below, including the mechanisms of groundwater movement and relevant aspects of hydrochemistry, in the context of bedrock formations present in England, Wales and Northern Ireland. The long term safety function of the geological formation is also controlled by changes in the broader environment with time such as the effects of plate tectonics and climate. These attributes are considered in other chapters within the Geosphere Status Report.

1.1.1 The international approach

International approaches to development of a GDF have utilised examples of these idealised end-member bedrock materials and are briefly described below. Both Sweden and Finland have developed GDF concepts utilising hard-rock host lithologies. The Swedish nuclear waste and management company, SKB, has selected a site at Forsmark for the development

of a 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 (Wahlgren, 2010). 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 (Lahti et al., 2009). Both these sites are strongly affected by both ductile and brittle tectonic and neotectonic deformation, which have been the focus of much of the investigation (Shaw et al., 2011).

France and Switzerland have both developed GDF concepts in very low-permeability Jurassic clay 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 very slow groundwater circulation (ANDRA, 2005). 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 (NAGRA, 2002).

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. The GDF comprises caverns excavated at a depth of about 800 m in bedded rock-salt (halite) of the Permian Salado Formation (e.g. Shaw et al., 2011). A similar setting is one of those being considered in Germany, where investigations in the Gorleben salt dome at a planned depth of 840 m have taken place (BMW, 2008). Plans to develop an additional GDF in volcanic rocks (welded ash-flow tuff) at Yucca Mountain in Nevada were cancelled in 2011.

1.2 CONTRIBUTION OF HYDROGEOLOGY AND HYDROCHEMISTRY TO POST-CLOSURE SAFETY AND CONSTRUCTION OF A GDF IN ENGLAND, WALES AND NORTHERN IRELAND

This section describes how key hydrogeological and hydrochemical attributes, such as permeability and groundwater chemistry contribute to the safety functions of isolation and containment and is based primarily on Watson et al (2007).

Isolation is largely a feature of the mechanical properties of the geological environment. However, containment is achieved by a combination of low groundwater flow rates within

the geological environment, retardation of any fugitive radionuclides and a non-corrosive chemical environment that helps preserve the integrity of storage vessels.

1.2.1 Groundwater flow rate

Groundwater flow is induced when there is a hydraulic gradient across a permeable geological formation. Consequently, low groundwater flow rates which are likely to inhibit transport of radionuclides from the GDF are a function of low host rock permeability and low hydraulic gradients. Hydraulic gradient is the difference in hydraulic head between two locations and controls the direction of groundwater flow. Higher hydraulic heads are associated with areas of groundwater recharge and lower heads with areas of groundwater discharge. 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 a fluid that takes account of both the porous medium (through the intrinsic permeability) and the properties of the fluid density and dynamic viscosity, which in turn are affected by other (depth dependent) parameters such as temperature. Primary permeability represents permeability that is provided by connected intergranular spaces whilst secondary permeability constitutes that provided by fractures. Many rock types exhibit 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 (Gillespie et al., 2011). Fractures can be enlarged by dissolution and may be open in the near surface as a result of stress relief, but tight at depth. The permeability properties may be modified significantly by the presence of mineralisation.

1.2.2 Solute transport and retardation

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 hydraulic gradient and hydraulic conductivity of the saturated rock. Diffusion, the process by which solutes move under influence of their kinetic activity in the direction of the concentration gradient, occurs in the absence of any bulk hydraulic movement of the solute. At low groundwater velocities, mechanical dispersion is negligible relative to molecular

diffusion. Where the permeability is less than 0.01 mD distinguishing between advection and diffusion becomes difficult (Falck and Bath, 1989). Diffusion is the dominant solute transport mechanism in unfractured clays and mudstones, where transport by moving groundwater is slow. In hard rocks, transport occurs via a combination of advection and diffusion, though fracture-borne advective flow typically dominates. Since diffusion is a slow process, the rate of radionuclide migration will be very much lower than in rocks where advective transport dominates, hence bedrock formations dominated by diffusive transport are likely to provide better containment.

Transport of radionuclides through host rocks is in large part controlled by the degree of retardation by adsorption. Retardation is a function of the surface properties of the host minerals and the hydrochemical environment and is most effective in rocks containing sorbents such as clays, metal oxides and organic matter. Adsorption capacity is also dependent on groundwater salinity, redox status and pH.

1.2.3 Corrosion/Chemical environment

The integrity of a 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 engineered barrier. In particular, groundwater salinity and oxidising capacity are important factors in determining its corrosion potential. The chemistry of deep groundwater is complex and specific to the geological environment, being dependent on the regional geological and hydrogeological environment, as well as the history of groundwater movement. In some permeable aquifers (e.g. sandstone), groundwater at depths around 200 m can be relatively fresh as a result of active groundwater flow. However, at greater depths and in less permeable rock types, where circulation is slow, groundwater is invariably 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. Some may be relatively enriched in Ca and Mg; high SO_4 concentrations are also a feature of some, depending on mineralogy of host rocks. Dissolved sulphide may be present under more strongly reducing conditions consistent with microbially-mediated sulphate reduction. Salinity, high concentrations of SO_4 and/or dissolved sulphide all enhance the metal-corroding potential of the groundwater and can be detrimental to the containment properties of the geological environment.

2 Bedrock geological materials and properties in England, Wales and Northern Ireland relevant to construction and post-closure safety of a GDF

Given that site selection in the UK will be based on voluntarism, geological environments available for the disposal facility will depend upon the locations offered by the communities choosing to be involved in the process of hosting a GDF in the UK. The approach taken in this chapter is to provide a brief account of the range of bedrock lithologies likely to be encountered in the subsurface of England, Wales and Northern Ireland to a depth of around 1km. These represent the fundamental building blocks of the geological environment and may contribute different textural, chemical and mineralogical properties 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 contribution of the geosphere we have developed a conceptual descriptive framework that seeks to place a variety of common natural geological materials in a matrix whose axes represent variation in the key properties of permeability and strength (Figure 1).

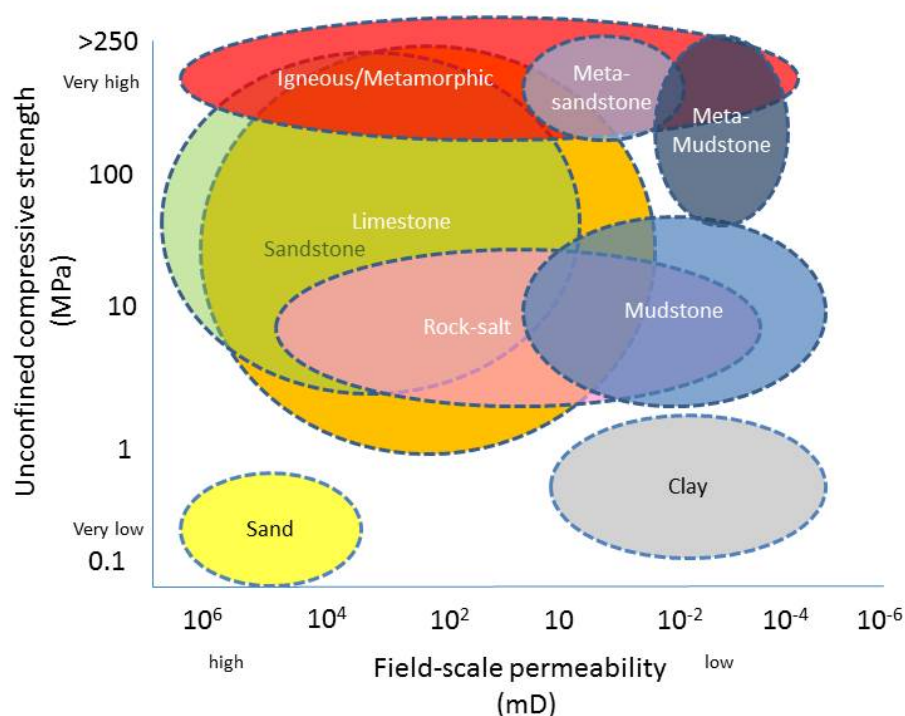


Figure 1. Indicative matrix of mechanical strength versus field scale permeability for key UK lithologies based on near surface determinations (both strength and permeability are likely to vary on the scale of a GDF dependant on distribution and density of secondary (fracture) permeability). Note: Limestone is shown in orange and sandstone shown in green.

The lithologies represented within this matrix are grouped into ‘soft rock’ and ‘evaporite’ which may have the capacity to act to both isolate a GDF and contain the radio nucleides potentially released, and ‘hard rock’. The latter is likely to have the capacity to isolate the GDF but may require the presence of low permeability cover rocks or an engineered solution to enhance containment. In general the ‘soft rock’ lithologies are characterised by low permeability and low strength, while the ‘hard rock’ lithologies may have higher strength, and be more prone to brittle deformation with interconnected mechanical discontinuities (fractures). The variations and controls on these properties are considered in the illustrative examples described below. The selected lithological classes are generalised from subdivisions represented on the British Geological Survey 1:1 000 000 series engineering

geology (bedrock) map of the UK (British Geological Survey, 2011) wherein these are related to lithological descriptions, including strength after BS5930: 1999.

Strength is described and classified in accordance with EN ISO 14688 parts 1 and 2 respectively. For this study, the widely used descriptor of Unconfined Compressive Strength (UCS) is adopted to classify rock strength at surface or near-surface. The rock strength description and terms are described in EN ISO 14689-1 and follow practice and terminology outlined in International Society for Rock Mechanics (1978) suggested methods.

The fields representing the common rock types are based on recognition of broadly contrasting divisions of both basic lithology and processes that may have modified them, including diagenesis and metamorphism since deposition. While not exhaustive, these are envisaged to cover most of the natural variability in potential host and cover rocks for a potential GDF site in England, Wales and Northern Ireland present at GDF depths (between 200 m and 1000 m) and occurring in sufficient volume for construction purposes. The following are considered to broadly capture the range of lithologies preserved 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 chapter, though details of failure mechanism are not covered in detail. The ‘sand’ class illustrated in Figure 1 is not considered as this material does not exist at GDF depths.

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

- i. lithological description to include mineral composition, texture, common penetrative structures and discontinuities;
- ii. important facies subdivisions, heterogeneity and layering;
- iii. key or characteristic geological / diagenetic history and consequences for properties and flow and transport;
- iv. mechanical properties summary related to lithology;
- v. porosity-permeability characteristics;
- vi. overview of hydrochemistry of typical groundwater and controls.

In providing these detailed descriptions it is necessary to utilise 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 not related to any site selection process.

2.1 EVAPORITE

2.1.1 Rock-salt

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 purpose of this chapter, we are primarily considering the occurrence of evaporite comprising rock-salt (halite) and potash (readily soluble potassium salts such as sylvite). Other evaporite deposits, including gypsum and anhydrite are not considered as they are not suitable for constructing a GDF due to high dissolution or swelling potential. Rock-salt may behave plastically in the shallow subsurface and has low porosity ($< 0.1\%$), low primary permeability (10^{-6} to 10^{-5} mD), field-scale permeability in the range $<10^{-3}$ to 10^4 mD (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 that have influenced these field test results), and solute movement is by diffusion. The fluids in rock-salt can be externally derived, i.e. originate from below the salt succession or enter as meteoric waters from above. Alternatively, they may be generated inside the salt body. The fluids are brines with salinity close to halite saturation. The preservation of halite over geological timescales indicates that groundwater flow is negligible. Adsorption of solutes to halite is generally very weak. Rock-salt is mechanically Weak (UCS 5 to 25 MPa). In these deposits mechanical excavation or dissolution methods are commonly employed to create caverns to extract salt as a mineral resource or for underground gas storage. Existence of pre-existing voids (mines) and its ongoing value as a resource are clear considerations in assessing the suitability of rock-salt for use in a GDF. Engineered cavities at depth are likely to be self-supporting but time dependant creep/flow behaviour is a consideration.

In England, Wales and Northern Ireland, most rock-salt is preserved within rocks of Triassic age (Mercia Mudstone Group) and is most widely developed in the Cheshire Basin, and to a

lesser extent in Lancashire, Worcestershire, Staffordshire, Dorset and Somerset. It is also present in Permian (Zechstein Group) rocks of NE England (e.g. Northolt and Highley, 1973; British Geological Survey, 2006). Rock-salt typically occurs in beds and units associated with mudstone that range from a few centimetres to hundreds of metres thick. Rock-salt does not crop out at 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'.

The Permian halites of the Zechstein Group were deposited in a rift system in an enclosed marine basin. The most extensively mined unit is known as the Boulby Halite (Figure 2), from which potash 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 around 1800 m. Elevated groundwater heads during the Devensian mean that the dissolution front and wet rockhead extend to depths of 300-400 m (Evans and Holloway, 2009).

The most significant rock-salt deposits are preserved in the Triassic Mercia Mudstone Group which was deposited in a series of discrete terrestrial basins, the most extensive of which is the Cheshire Basin of northern England and parts of Wales (Hounslow and Ruffell, 2006). Here, the Mercia Mudstone Group largely comprises units of mudstone and siltstone that are locally interlayered with thinner halite beds as well as two significant halite units: the Northwich Halite Member, up to around 280 m thick, and Wilkesley Halite Member, up to around 400m thick (Plant et al., 1999). Both rock-salt units are interlayered with units of mudstone and locally sandstone (Figure 2). Wet rock head generally extends to 50-60 m, but has been recorded down to depths of about 180 m (Evans and Holloway, 2009), being exacerbated by brine pumping.



Figure. 2. Core from Northwich Victoria Infirmary Borehole (SJ67SE/137), Triassic Northwich Halite Formation. Interlayered mudstone and halite (P749044)

2.2 SOFT ROCK LITHOLOGIES

2.2.1 Clay

This class includes fine-grained clastic sedimentary rock comprising claystone, mudstone and siltstone that have not undergone significant sedimentary burial-related chemical or physical alteration (diagenesis) as seen in ‘mudstone formations’ (below). Clay bedrock formations are often over-consolidated and 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 and solute transport occur by diffusion. 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 up or downwards towards more permeable over- and underlying rocks. Where characterised by plastic behaviour, any fractures present should not be

transmissive. These materials are relatively easy to excavate (Tunnel Boring Machine or mechanical excavators) 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 on a small to medium scale.

Clay lithologies are preserved as two main facies, classified on the prevailing conditions at the depositional interface, referred to as oxic and dysoxic facies. Oxic facies were deposited when free circulation of oxygen allowed development of a thriving benthic infauna. The resulting sediment tends to be burrow-mottled, and critically, bedding and lamination are frequently destroyed sometimes giving rise to a high degree of homogeneity. In contrast, dysoxic facies were deposited at times of relatively low oxygenation and the resulting deposits are typically unbioturbated and preserve original depositional structures (lamination) and organic material.

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 (Ellison et al., 2004; Entwisle et al., 2013).

The Cenozoic clay formations tend to be relatively thin, in 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 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 3). Locally, dysoxic facies units of laminated clay are preserved.



Figure 3. Rootlet traces in the basal Reading Formation, Alum Bay (P692184).

Post depositional pedogenesis has formed mineralised silcrete and calcrete ‘hard bands’. The clay often has a blocky texture defined by numerous discontinuities formed as the result of repeated expansion and contraction during periods of subaerial wetting and drying.

The deposits typically comprise clay minerals with a subordinate proportion of silicate minerals such as quartz, glauconite and alkali feldspar as well as some mica. The clays themselves include smectite, illite, chlorite and kaolinite. Nodules of apatite are locally preserved as a product of diagenetic breakdown and re-precipitation of phosphatic fossil material. The predominance of smectite 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), although this may be beneficial to containment. Authigenic pyrite is often present in dysoxic facies, the presence of which also represents a significant design consideration

because of the production of highly acidic leachate on weathering that has the ability to attack concrete structures.

Dewhurst et al. (1998) quote porosities for Cenozoic clay of 43-48% and intrinsic permeabilities of 10^{-2} and 4×10^4 mD for two samples. At the formation scale permeability is increased by fracturing, and average values of 1mD have been quoted for the London Basin (Water Resources Board, 1972). The chemistry of groundwater from the London Clay at depths of between 5 and 57 m for a site at Bradwell indicate pH between 7 and 9 and variably high sulphate (Bath et al., 1989).

2.2.2 Mudstone

This class includes claystone, mudstone and siltstone lithologies comprising clay minerals and a detrital framework of silicate grains and is likely to be lithified having undergone alteration such as growth of cement and recrystallisation of primary clay minerals during initial sedimentary burial (diagenesis). It generally has moderate to high porosity (1 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 up or downwards towards more permeable over- and under-lying rocks.

Mudstones may contain large to small scale fractures that may affect permeability at the large and small scale. They are typically Weak to Medium Strong (UCS 5 to 50 MPa) and moderately easy to excavate with a TBM or mechanical excavator and do not tend to require blasting. They have a moderate propensity for heave, swelling and creep behaviour are likely at GDF depths and may require support in engineered cavities.

Mudstone is a commonly occurring sedimentary rock that is present throughout the geological record of England, Wales and Northern Ireland. It is 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 comprises a fine grained sedimentary rock with more than 50% siliciclastic fragments in which at least 75% of the clasts are less than 32 μm , including both silt grade and clay grade material. They typically have components of detrital clay minerals as well as authigenic clay minerals grown during diagenesis and may have an organic component. 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 is strongly controlled by depositional process and subsequent diagenesis.

For the purpose 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. 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 (e.g. Horton et al., 1995). The lower Peterborough Member comprises greenish blocky mudstone with interbeds of fissile bituminous mudstone and locally persistent horizons of argillaceous micritic limestone nodules and beds. This member is a historically important brick clay resource (Figure 4).



Figure 4. King's Dyke Pit, Whittlesey, near Peterborough. Excavation in Peterborough Member of the Oxford Clay Formation (P802440).

Petrographic analysis of the member reveals it to comprise largely quartz and illite, with subordinate chlorite, kaolinite, K-feldspar and plagioclase, and variable amounts of calcite and siderite (Norry et al., 1994). 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 (Belin and Kenig, 1994).

Because of its low permeability (10^{-4} to 1 mD Hallam et al., 1991), 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 (Barron et al., 2010). Measurement of average groundwater heads in Oxfordshire indicates upwards movement into overlying more permeable strata (Alexander, 1983). Engineering considerations associated with the Oxford Clay Formation, include concrete attack resulting from pyrite oxidation and shrink-swell behaviour.

2.3 HARD ROCK LITHOLOGIES

2.3.1 Very low grade metamudstone

A subdivision of the former, these are sedimentary rocks that are typically older than fine grained 'mudstone' and 'clay' classes and have undergone significant post depositional modification including diagenesis, very low grade metamorphism and penetrative structural deformation to form folds and tectonic fabrics that have significantly changed the texture, strength and permeability characteristics of the metamudstones. They are typically Strong to Very Strong (UCS 50 to 250 MPa) and can display strength anisotropy on a GDF scale where tectonic fabrics and discontinuities are developed. Metamudstone generally has low porosity (<5 %) and low primary permeability (10^{-8} to 10^{-3} mD) with solute transport by diffusion, but field scale permeability is generally orders of magnitude higher due to the presence of fractures (10^{-4} to 10^{-3} mD). 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 rocks in England, Wales and Northern Ireland that fall into this division are of Palaeozoic age and have been subject to Silurian (Caledonian) and Carboniferous (Variscan) penetrative tectonism. The principal areas of exposure are in Wales, the south-west of England and Cumbria. In these regions, the deposits form parts of thick marine basinal sequences. Perhaps the best characterised of these is the Lower Palaeozoic Welsh Basin (e.g. Davies et al., 1997). Here, metamudstone units preserve more than 3500 m of strata and make up around 60% of the entire basinal succession. Most of these mudstones were deposited in turbidite fans and are locally interlayered on a cm to m scale with beds of metasandstone and on a 100's of metres scale with metasandstone-dominated and extrusive volcanic units.

Individual turbidite event beds typically comprise mm-scale fine sand or silt overlain by around 2-15 cm of turbidite mudstone, in turn overlain by cm-scale laminated hemipelagic mudstone. Turbidite event beds are often stacked to a thickness of several hundred metres giving the rock mass a monotonous rhythmic character. Some metamudstone units contain slumped strata, up to 600 m thick, which are often relatively destratified and homogenised. Both oxic and dysoxic facies are preserved. In oxic facies, diagenetic oxidation of phosphatic fossil material is accompanied by crystallisation of calcium phosphate (apatite) cements and nodules that increase the overall strength of this facies. In dysoxic facies, organic material is typically preserved within hemipelagic horizons (Figure 5) and diagenetic and metamorphic growth of minerals such as pyrite and the rare-earth phosphate monazite are common (Milodowski et al., 1991).

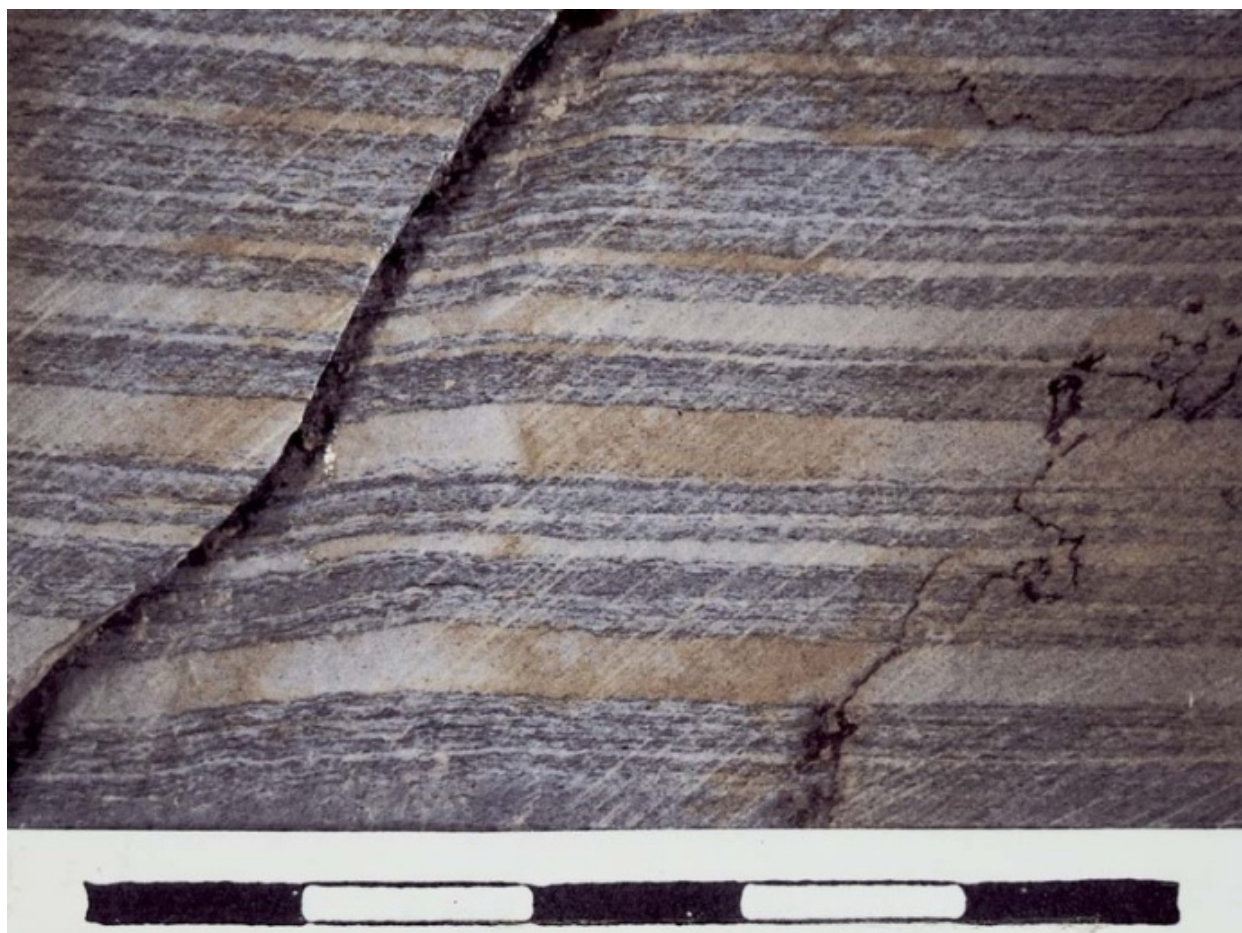


Figure 5. Dysoxic facies metamudstone of the Silurian Caerau Mudstones Formation comprising interbedded turbidite mudstones and laminated hemipelagite (P708378).

The critical process that distinguishes this class from other mudstones is the influence of very low grade metamorphism under late diagenetic zone, anchizone and epizone conditions (e.g. Robinson and Bevins, 1986; Roberts and Merriman, 1985). During both sedimentary burial and tectonic shortening, the basinal mudstones have been subject to strong directed stress and elevated temperature, up to 330-380°C, and pressure. In response to these changes in conditions, detrital clay minerals and white mica have recrystallised into larger crystals of illite and chlorite aligned normal to the principal compressive stress at that time to form a slaty cleavage microfabric (Merriman et al., 1990).

2.3.2 Sandstone

This is a commonly occurring sedimentary rock that is present throughout the geological record of England, Wales and Northern Ireland. It is deposited in terrestrial settings; including aeolian dunes and rivers, and in marine settings including shorefaces, shelf or

platforms and as fans or lobes forming basin slope aprons. In general sandstone consists of clasts ranging in size from 32 μm to 2 mm that are most commonly quartz, feldspar or lithic fragments; with variably developed intergranular cement, most commonly comprising calcium carbonate or silica that is formed during diagenesis (Hallsworth and Knox, 1999). This material is commonly arranged in beds of variable thickness that often preserve sedimentary structures such as grading or cross-bedding that are indicative of its mode of deposition. These are generally mechanically Weak to Strong (UCS 1 to 50 MPa), although poorly-consolidated sand (UCS <1 MPa) may also occur at GDF depths in some formations. They have variable porosity (2-50%) and moderate to high primary permeability (10^{-3} to 10^4 mD) with solute transport by advection. Fracture permeability may be important in more cemented horizons and the range of field-scale permeabilities is typically higher (10^{-5} to 10^5 mD). Sorption is likely to occur, depending on abundance of clay minerals and metal oxide. Sandstone generally exhibits 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 including bedding thickness, fracture spacing and orientation. Cavities may require support dependent on rock mass properties and local stress conditions. Fractures varying on a very wide range of scales are often present.

For the purpose of this study we have chosen an example from the Triassic Sherwood Sandstone Group that is relatively widespread and well described, largely because of its importance as an aquifer. It 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 (Macchi, 1991). 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 6).



Figure 6. St Bees Sandstone Formation showing sheet sandstones near the base of the quarry overlain by channelised sandstones (P621360).

Diagenesis includes precipitation of authigenic minerals and cements in pore spaces and fractures including anhydrite, calcite, dolomite, haematite, barite, kaolinite and illite clays (Milodowski et al., 1998). The current 3.7-27.2% porosity in the formation is considered largely secondary and attributed to dissolution of carbonate by modern groundwaters (Allen et al., 1997; Strong et al., 1994). Permeabilities measured on core samples and in boreholes range from below 10^{-2} up to 10^3 mD (Bloomfield and Williams, 1995; Chaplow, 1996). 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 (Barnes et al., 1998; Hough et al., 2006).

Salinity of groundwater in the Triassic Sherwood Sandstone varies widely depending on local structural and geological conditions (e.g. Edmunds et al., 1982; Tellam, 1995). Remarkably fresh groundwater has been observed at depths up to 500 m in the confined Sherwood

Sandstone of the East Midlands. In the Cheshire Basin and Merseyside, saline groundwater exists at depths of typically 200 m but can be shallower depending on groundwater flow paths, typically influenced by faulting (Brassington and Taylor, 2012; Seymour et al., 2006). Groundwater is anoxic in deep flow paths. Groundwater from the Sherwood Sandstone can possess high concentrations of dissolved SO_4 through dissolution of gypsum or anhydrite. Bacterially-mediated sulphate reduction has been observed in groundwater at depth at some locations.

2.3.3 Very low grade metasandstone

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 class, most of the rocks considered to be metasandstone are of Palaeozoic age and have been subject to Silurian (Caledonian) and Carboniferous (Variscan) penetrative tectonism. The example presented herein is from the Cwmystwyth Grits Group of the Lower Palaeozoic Welsh Basin (e.g. Davies et al., 1997). Here, metasandstone units preserve more than 2000 m of strata and make up around 40% of the entire basinal succession. Most of these metasandstones were deposited from sediment rich, submarine density flows in units generally known as turbidites. Sand grade clastic turbidites commonly form lobes or channels and comprise stacks, often many hundreds of metres thick of individual turbidite event beds.

Within the Cwmystwyth Grits Group, typical turbidite units comprise graded beds of metasandstone ranging from 2 cm to 30 cm in thickness, or in parts, these can reach around 2 m in thickness. Individual turbidite event beds are often overlain by thin, cm-scale, laminated hemipelagite, although this may be eroded by deposition of the subsequent unit, and may be of either oxic or dysoxic facies. Stacking of individual graded event beds can impart a multilayer appearance to the rocks on a cm- to metre-scale in which the proportion of metasandstone may vary between around 10% and 60% (Figure 7; Cave and Hains, 1986).



Figure 7. Folded succession of interbedded very low grade metasandstone and metamudstone from the Cardigan Bay coast (P662414).

The Cwmystwyth Grits Group largely comprise quartz-rich sandstone with subordinate alkali feldspar clasts and detrital illite or chlorite. Some variants, termed ‘high matrix sandstone’ are dominated by detrital chlorite and illite and may have matrix-supported textures. During regional deformation and very low grade metamorphism the metasandstones have developed slaty cleavage microfabric and typically quartz has remobilised and recrystallised to reduce the original porosity. The intergranular permeability of the Cwmystwyth Grits is minimal and water movement and storage is controlled by the degree of fracturing and fracture connectivity which is heterogeneous at all scales (Shand et al., 2005), however the amount of fracturing is greatest in the shallow part of the formation due to weathering. Cleavage planes typically have a cm-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 km- to m-scale so that beds are typically moderately-inclined to sub-vertical.

2.3.4 Limestone

This lithology comprises beds and lithostratigraphic units dominated by calcium or magnesium carbonate minerals, largely primarily derived from biogenic sources (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 to 50%), primary permeability (10^{-7} to 10^3 mD) and field-scale permeability (10^{-1} to 10^6 mD). Limestones include formations, such as Cretaceous Chalk, which can be very weak, highly porous and permeable where fractured, or Carboniferous Limestone which includes significant units that are very strong and typically have 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 and/or by diffusion through the low permeability 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.

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 (e.g. Mortimore et al., 2001; Figure 8). Because of the planktonic nature of the original algae, chalk ooze is deposited across a variety of marine settings and water depths.



Figure 8. Chalk cliffs at Flamborough Head (P006782).

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 (Bloomfield, 1996), 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 (Mortimore et al., 2011). The Chalk forms an important dual porosity aquifer. Small pore throat diameters inhibit gravity drainage so that primary permeability is very low (1 mD; Allen et al., 1997; Bloomfield et al., 1995) 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; Allen et al, 1997).

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 trapping and binding of sediments in microbial mats as well as re-sedimented deposits (Stow, 2005). 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 mm 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 rapid flow of water; hence they can be vulnerable to contamination.

2.3.5 Extrusive igneous rocks

This class comprises beds, lithostratigraphic units and successions of erupted volcanic debris and their re-sedimented products. These mostly occur as part of the older geological record in the UK and are typically Very Strong to Extremely Strong (UCS 100 to >250 MPa) and generally have low to moderate porosity (0 to 50%) and 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. 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, Wales and Northern Ireland 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, but also include the Cenozoic Antrim plateau basalts of Northern Ireland. In general, the outcrop record in these areas consists of interlayered units of largely crystalline tuffs and very low grade metasedimentary rocks. These have been subject to tectonic deformation and are folded so that primary layering is often steeply inclined, and preserve complex discontinuity networks comprising cleavage, fractures and faults and joints.

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 extrusive igneous rocks (e.g. Howells and Smith, 1997; Millward et al., 2000). 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 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 (cf. Branney and Kokelaar, 2002). 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 (fiamme; Figure 9). The volumetrically dominant felsic tuffs typically comprise an admixture of siltstone and sandstone lithic fragments, volcanic glass shards and feldspar crystals in a matrix of sericite and chlorite. Shards and fiamme are generally devitrified and recrystallised to fine-grained quartz mosaics. Scattered brecciated horizons and pipes and layers of silica nodules reflect vapour escape crystallisation during and immediately after deposition.



Figure 9. Silicified welded ash-flow tuff with prominent fiamme, Snowdon Volcanic Group (P213433).

Under conditions of very low grade metamorphism (Roberts and Merriman, 1985) clay minerals from devitrified vitric matrix recrystallised to form sericite-chlorite cleavage.

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 (Chaplow, 1996). Most of the fractures intersected by the boreholes had no detectable flow, possibly explained by fracture-sealing by mineralisation.

2.3.6 Intrusive Igneous rocks

These are rocks that have originated as magmas, the product of partial melting in the lower crust or mantle that have been emplaced at higher levels within the crust. They form large masses (plutons) or smaller sheet-like bodies (dykes and sills). They are locally present at

surface in England, Wales and Northern Ireland where they have intruded into the sedimentary cover, but are thought to be more widespread at depth. They comprise Very Strong to Extremely Strong (UCS100 to >250 MPa) crystalline rocks which have generally low to moderate porosity (0 to 10%) 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 due to the orientation of fracture systems. Excavations in intrusive igneous rock are likely to require blasting and may be self-supporting in deep engineered cavities but strongly controlled by local stress conditions, fracture characteristics and strength.

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. $30^{\circ}\text{C km}^{-1}$) and has been the subject of geothermal energy exploration and extensive geological characterisation (e.g. Batchelor, 1984; Parker, 1992).

The Carnmenellis Granite, along with the other elements of the Cornubian Batholith was intruded during Permian times during the latter stages of the Variscan Orogeny. It forms a roughly circular outcrop, interpreted and modelled from geophysical survey data to be more extensive at depth (e.g. Taylor, 2007; Figure 10). The pluton comprises a number of 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 (Leveridge et al., 1990).



Figure 10. Example of alkali-feldspar megacrystic granite from the Cornubian Batholith (P751221).

Intrusion was accompanied by thermal metamorphism in the sedimentary host rock as well as widespread pegmatite veining and hydrothermal alteration that largely controlled the location and species of 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 (Edmunds et al., 1984). 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.

Porosity measurements from boreholes in the Carnmenellis Granite, at depths of up to 1780 m range between 0.25-1.2% (British Geological Survey, 1990). 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 of 2 to 89 mg/l. Springs of saline groundwater are known to occur in tin mines at depths of over 300 m (British Geological Survey, 1990). 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.

2.3.7 Metamorphic rocks

Metamorphic rocks comprise crystalline rock units that have been formed by alteration of sedimentary and igneous protoliths in response to changes in pressure and temperature. These changes are generally brought about by deep burial during tectonic thickening of the earth's crust, where rocks at surface may be buried in the course of tectonic deformation to many 10's of km, or by proximity to an anomalous heat source, such as an igneous intrusion. These changes drive chemical reactions in the component minerals in the protolith to form more stable forms and are influenced by passage of gases or fluids through the rock mass. Metamorphic rocks 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 strongly dependent on local stress conditions, fracture characteristics and strength.

Metamorphic rocks that result from tectonic burial processes usually undergo extended episodes of structural deformation and the resulting textures reflect these two processes happening together. Typical textures preserved in metamorphic rocks from England, Wales and Northern Ireland are: schist, where the dominant feature of the rocks is a planar fabric defined by alignment of phyllosilicate minerals; gneiss, where the dominant textural feature is a compositional banding; and granofels, which tend to be crystalline rocks with no systematic layering (Robertson, 1999). Diagnostic mineral assemblages that are preserved are typically related to the degree of metamorphism expressed in changes in temperature and pressure described through a system of metamorphic facies. Most of the metamorphic rocks known at surface in England, Wales and Northern Ireland reflect metamorphism under

moderate mid-crustal conditions of greenschist and amphibolites facies where temperature ranged between around 400 to 750°C and pressure between around 2 to 10 kbar. There are also some less common exposures of blueschist facies rocks which crystallised in response to high pressure and relatively low temperatures.

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. For example, the Mona Complex of Anglesey (Greenly, 1919) comprises a number of dominantly metasedimentary units of contrasting composition. These include sparse exposures of biotite-garnet-sillimanite gneiss representative of metamorphism of sedimentary protoliths under high amphibolite facies conditions (Carney et al., 2000); thinly interlayered psammitic (quartzofeldspathic) and pelitic (mica-rich) metasedimentary schists that locally preserve sedimentary features (Figure 11); lenses of metamafic rocks with distinctive barroisite and glaucophane-bearing blueschist facies mineral assemblages (Dallmeyer and Gibbons, 1987).



Figure 11. Tectonic folds in psammitic metasedimentary rock, Anglesey.

3 Summary

This chapter describes the contribution of the Geosphere, which in combination with engineered structures, barrier/backfill systems and the waste-form, deliver the GDF safety functions of containment and isolation. The relevant Geosphere properties of hydrogeology, hydrochemistry and bedrock lithology and physical properties are described. Together these make up the geological environment which acts as part of the multi-barrier GDF concept. The properties of bedrock materials in England, Wales and Northern Ireland are described and illustrated with reference example formations from the geological record. The geological properties of these are summarised in Table 1.

Class	Lithology	Porosity (%)	Primary permeability (mD)	Field-scale permeability (mD)	Solute transport mechanism	Unconfined Strength (MPa)	Compressive	Stability in deep engineered cavities
Evaporite								
Rock-salt	Thin to thick units of halite and potash with beds and units of mudstone	low (<0.1)	low (10^{-6} to 10^{-5})	low ($<10^{-3}$ to 10^4)	Diffusion	Weak (5 to 25)		Self-supporting, subject to creep
Soft rock								
Clay	Units of plastic claystone and mudstone	high (40-70)	low (10^{-5} to 1)	low (10^{-5} to 1)	Diffusion	Very Weak to Weak (1.15 to 25)		Support required, subject to creep
Mudstone	Units of lithified claystone, mudstone and siltstone	variable (1 to 40)	variable (10^{-4} to 100)	low (10^{-5} to 1)	Diffusion	Weak to Medium Strong (5-50)		May require support
Hard rock								
Very low grade metamudstone	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 (50-250)		May require support
Sandstone	Units of lithified sandstone	variable (2 to 50)	variable (10^{-3} to 10^4)	variable (10^{-5} to 10^5)	Advection	Weak to Strong (1-50)		May require support
Very low grade metasandstone	Recrystallised sandstone lithologies with a spaced slaty cleavage	low to moderate (<15)	variable (10^{-4} to 100)	(10^{-2} to 10)	Advection	Medium Strong to Extremely Strong (25 to >250)		May require support
Limestone	Units of calcium or 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)		May require support
Extrusive igneous rock	Units of erupted volcanic debris	variable (0 to 50)	low (10^{-5} to 10)	(10^{-1} to 10^6)	Advection	Very Strong to Extremely Strong (100 to >250)		High (unfractured) to Low (fractured)
Intrusive igneous rock	Plutons, dykes and sills of crystalline rock	low to moderate (0-10)	low (10^{-8} to 1)	(10^{-5} to 10^5)	Advection	Very Strong to Extremely Strong (100 to >250)		High (unfractured) to Low (fractured)
Metamorphic rock	Units of schist, gneiss or granofels	low to moderate (0-10)	low (10^{-7} to 1)	(10^{-5} to 10^5)	Advection	Strong to Extremely Strong (50 to >250)		High (unfractured) to Low (fractured)

Table 1. Summary properties of lithological classes of typical geological formations in England, Wales and Northern Ireland. Assessment of stability in deep engineered cavities is qualitative and likely to vary with depth, stress conditions, fracture density and type and strength. Porosity and permeability values after: Allen et al. (1997), Bloomfield and Williams (1995), Bloomfield et al. (1995), Brace (1980), Cardenas et al. (1999), Chaplow (1996), Clauser (1992), Davies and DeWiest (1966), Dewhurst et al. (1998), Freeze and Cherry (1979), Hallam et al. (1991), Horseman et al. (1982), Jones et al. (2000), Manning and Ingbritsen (1999), Schulze et al. (2001), Water Resources Board (1972).

References

- Allen, D.J., Brewerton, L.J., Coleby, L.M., Gibbs, B.R., Lewis, M.A., MacDonald, A.M., Wagstaff, S.J., Williams, A.T., Barker, J.A., Bird, M.J., Bloomfield, J.P., Chenery, C.S., Talbot, J.C. and Robinson, V.K. 1997. The physical properties of major aquifers in England and Wales. *British Geological Survey Technical Report* WD/97/34. 312pp.
- Alexander, J. 1983. The groundwater regime of the Harwell region. British Geological Survey Reoprt FLPU 83-10.
- ANDRA, 2005. Dossier Argile 3. The geological medium: the Meuse/Haute Marne site. *ANDRA report series*.
- Barnes, R.P., Dee, S.J., Sanderson, D.J. and Bowden, R.A. 1998. Interpretation of structural domains in discontinuity data from Nirex deep boreholes at Sellafield. *Proceedings of the Yorkshire Geological Society*, 52, 177-187.
- Batchelor, A.S. 1984. Hot Dry rock geothermal exploitation in the United Kingdom. *Modern Geology*, 9, 1-41.
- Bath, A.H., Ross, C.A.M., Entwisle, D., Cave, M.R., Green, K.A., Reeder, S. and Fry, M. 1989. Hydrochemistry of porewaters from London Clay, Lower London Tertiaries and Chalk at Bradwell site. *British Geological Survey Report* WE/89/26, 152pp.
- Barron, A.J.M., Sumbler, M.G., Morigi, A.N., Reeves, H.J., Benham, A.J., Entwisle, D.C. and Gale, I.N. 2010. Geology of the Bedford district –a brief explanation of the geological map. *Sheet Explanation of the British Geological Survey*. 1:50 000 Sheet 203 Bedford (England and Wales).
- Belin, S. And Kenig, F. 1994. Petrographic analysis of organo-mineral relationships: depositional conditions of the Oxford Clay Formation (Jurassic), UK. *Journal of the Geological society, London*, 151, 153-160.
- Bloomfield, J.P. 1996. Characterization of hydrogeologically significant fracture distributions in the Chalk at Fair Cross, Berkshire, UK. *Journal of Hydrology*, 184, (3-4), 355-379
- Bloomfield, J.P. and Williams, A.T. 1995. An empirical liquid permeability gas permeability correlation for use in aquifer properties studies. *Quarterly Journal of Engineering Geology*, 28(S2), S143-S150.
- Bloomfield, J.P., Brewerton, L.J. and Allen, D.J. 1995. Regional trends in matrix porosity and dry density of the chalk of England. *Quarterly Journal of Engineering Geology*, 28(S2), S131-S142.
- Brace, W.F. 1980. Permeability of crystalline and argillaceous rocks. *International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts*, 17, 241-251.
- Branney, M.J. and Kokelaar, B.P. 2002. Pyroclastic density currents and the sedimentation of ignimbrites. *Geological society of London Memoir* 27.

- Brassington, F.C. and Taylor, R. 2012. A comparison of field methods used to define saline-fresh groundwater interfaces at two sites in North West England. *Quarterly Journal of Engineering Geology and Hydrogeology*, 45, 173-181.
- British Geological Survey, 1990, The Carnmenellis Granite-hydrogeological, hydrogeochemical and geothermal characteristics, 1:50000.
- British Geological Survey. 2006. *Salt*. Mineral Planning Factsheet. ODPM-BGS.
- British Geological Survey, 2011. Engineering Geology (Bedrock) map of the United Kingdom. British Geological Survey.
- British Standard BS5930. 1999. Code of Practice for Site Investigations, incorporating Amendment 2 (2010). British Standards Institution, London.
- Cardenas. M., LeCompte, C. and Gua, G. 1999. Estimation of permeability of disturbed halite using inverse modelling. *Groundwater*, 37, 539-545.
- Carney, J.N., Horák, J.M., Pharaoh, T.C., Gibbons, W., Wilson, D., Barclay, W.J., Bevins, R.E. 2000. *Precambrian rocks of England and Wales*, Geological Conservation Review Series No. 20, Joint Nature conservation Committee, Peterborough.
- Cave, R. and Hains, B.A. 1986. Geology of the country between Aberystwyth and Machynlleth. *Memoir of the British Geological Survey*, Sheet 163 (England and Wales).
- Chaplow, R. 1996. The geology and hydrogeology of Sellafield: an overview. In: The Geology and Hydrogeology of the Sellafield area. *Quarterly Journal of Engineering Geology*, 29, 1-12.
- Chapman, N. and Hooper, A. 2012. The disposal of radioactive wastes underground. *Proceedings of the Geologists' Association*, 123, 46-63.
- Clauser, C. 1992. Permeability of crystalline rocks, *EOS transactions of the American Geophysical Union*, 73, 233-240.
- Dallmeyer, R.D. and Gibbons, W. 1987. The age of blueschist metamorphism in Anglesey, North Wales: evidence from $^{40}\text{Ar}/^{39}\text{Ar}$ mineral dates of the Penmynydd schists. *Journal of the Geological Society of London*, 144, 843-50.
- Davies, S.N. and deWiest, R.J.M. 1966. *Hydrogeology*. John Wiley and Sons.
- Davies, J.R., Fletcher, C.J.N., Waters, R.A., Wilson, D., Woodhall, D.G. and Zalasiewicz, J.A. 1997. Geology of the country around Llanilar and Rhayader. *Memoir of the British Geological Survey*, Sheet 178 and 179 (England and Wales).
- Dewhurst, D.N., Aplin, A.C., Sarda, J-P. and Yang, Y, 1998, Compaction-driven evolution of porosity and permeability in natural mudstones: An experimental study. *Journal of Geophysical Research*, 103, 651-661.
- Edmunds, W.M., Andrews, J.N., Burgess, W.G., Kay, R.L.F. and Lee, D.J. 1984. The evolution of saline and thermal groundwaters in the Carnmenellis Granite. *Mineralogical Magazine*, 48, 407-424.

Ellison, R.A., Woods, M.A., Allen, D.J., Forster, A., Pharoah, T.C. and King, C. 2004. Geology of London. *Memoir of the British Geological Survey*, Sheets 256 (North London), 257 (Romford), 270 (South London) and 271 (Dartford) (England and Wales).

EN ISO 14689-1. 2003. Geotechnical Investigation and Testing –Identification and classification of rock. Part 1 Identification and description. *British Standards Institution*, London.

Entwisle, D.C., Hobbs, P.R.N., Northmore, K.J., Skipper, J., Raines, M.R., Self, S.J., Ellison, R.A. and Jones, L.D. 2013. Engineering Geology of British Rocks and Soils -Lambeth Group. *British Geological Survey Open Report*, OR/13/006. 316pp.

Environment Agency, 2009, Technical issues associated with deep repositories for radioactive waste in different geological environments, Science Report SC060054/SR1.

Evans, D.J. and Holloway, S. 2009. A review of onshore UK salt deposits and their potential for underground gas storage. In: Evans, D.J. and Chadwick, R.A. (eds.) *Underground Gas Storage: worldwide Experiences and Future Development in the UK and Europe. Geological Society, London, Special Publications*, 313, 215-224.

Falck, W.E. and Bath, A.H. 1989. Evaluation of vertical changes in groundwater chloride and stable isotope compositions in coastal London Clay. *British Geological Survey Report*, WE/89/10C.

Freeze, R.A. and Cherry, J.A. 1979. *Groundwater*. Prentice-Hall Inc.

Gillespie, M.R., Barnes, R.P. and Milodowski, A.E. 2011. British Geological Survey scheme for classifying discontinuities and fillings. *British Geological Survey Research Report*, RR/10/05. 56pp.

Greenly, E. 1919. The Geology of Anglesey. *Memoir (District) Geological survey of Great Britain*. HMSO, London. 980pp.

Hallam, J.R., Brightman, M.A., Jackson, P.D. and Sen, M.A. 1991. Summary and conclusions of the faults in clay project. *British Geological Survey Report* WE/91/26.

Hallsworth, C.R. and Knox, R.W.O'B. 1999. BGS Rock Classification Scheme Volume 3: Classification of sediments and sedimentary rocks. *British Geological Survey Research Report*, RR/99/03. 44pp.

Hounslow, M.W. and Ruffell, A. 2006 Triassic: Seasonal rivers, deserts and saline lakes. Ch 13 in Brenchley, P.J. and Rawson, P.F. (eds) *The Geology of England and Wales*. The Geological Society, London, 295-324.

Horseman, S.T., Hobbs, P., McEwen, T.J., Avery, L. and Forster, A. 1982 Basic geotechnical properties of core from the Harwell boreholes. *British Geological Survey Report* ENPU 82-7.

Horton, A., Sumblar, M.G., Cox, B.M. and Ambrose, K. 1995. Geology of the country around Thame. *Memoir of the British Geological Survey*, Sheet 237 (England and Wales).

Howells, M.F. and Smith M. 1997. Geology of the country around Snowdon. *Memoir of the British Geological Survey*, Sheet 119 (England and Wales).

Hough, E., Pearce, J., Kemp, S. and Williams, G.M. 2006 An investigation of some sediment-filled fractures within redbed sandstones of the UK. *Proceedings of the Yorkshire Geological Society*, 56, 41-53.

International Atomic Energy Authority 2011. Safety Standards Series No. SSG-14: Geological Disposal facilities for Radioactive Waste.

International Society for Rock Mechanics. 1978. Suggested methods for the quantitative description of discontinuities in rock masses. Commission on standardisation of laboratory and field tests. *International Journal of Rock Mechanics, Mining Science and Geomechanics Abstracts*, 15, 319-368.

Jones, H.K., Morris, B.L., Cheney, C.S., Brewerton, L.J., Merrin, P.D., Lewis, M.A., MacDonald, A.M., Coleby, L.M., Talbot, J.C., McKenzie, A.A., Bird, M.J., Cunningham, J. and Robinson, V.K. 2000. The physical properties of minor aquifers in England and Wales. *British Geological Survey Report* WD/00/04.

Lahti, M., Ahokas, T., Nordbäck, N., Paananen, M., Paulamäki, S., Vaittinen, T. 2009. *The ONKALO Area Model, Version 1.1*. Posiva Oy Working Report 2009-113. 130pp.

Leveridge, B.E., Holder, M.T. and Goode, A.J.J. 1990. Geology of the country around Falmouth. *Memoir of the British Geological Survey*, Sheet 352 (England and Wales).

Macchi, L. 1991. *A field guide to the continental Permo-Triassic Rocks of Cumbria and northwest Cheshire*. Liverpool Geological Society, Liverpool.

Manning, C.E. and Ingrbritsen, S.E. 1999. Permeability of the continental crust: implications of geothermal data and metamorphic systems. *Reviews of Geophysics*, 37, 127-150.

Merriman, R.J., Roberts, B. and Peacor, D.R. 1990. A transmission electron microscope study of white mica crystallite size distribution in a mudstone to slate transitional sequence, North Wales, UK. *Contributions to Mineralogy and Petrology*, 106, 27-40.

Millward, D., Johnson, E.W., Beddoe-Stephens, B., Young, B., Kneller, B.C., Lee, M.K. and Fortey, N.J. 2000. Geology of the Ambleside district. *Memoir of the British Geological Survey*, Sheet 38 (England and Wales).

Milodowski, A.E. and Zalasiewicz, J.A. 1991. Redistribution of rare earth elements during diagenesis of turbidite/hemipelagite mudrock sequences of Llandovery age from Central Wales. 101-124 in *Developments in sedimentary provenance studies*. Morton, A.C., Todd, S.P. and Hangton, P.D. (editors). *Special Publication of the Geological Society, London*, 57.

Milodowski, A.E., Gillespie, M.R., Naden, J. Fortey, N.J., Shepherd, T.J., Pearce, J.M. and Metcalfe, R. 1998. The petrology and paragenesis of fracture mineralisation in the Sellafield area, west Cumbria. *Proceedings of the Yorkshire Geological Society*, 52, 215-241.

Mortimore, R.N., Wood, C.J., Gallois, R.W. 2001. *British Upper Cretaceous Stratigraphy*. Geological Conservation Review Series 23. Joint Nature conservation Committee, Peterborough.

Mortimore, R., Newman, T.G., Royse, K., Scholes, H. and Lawrence, U. 2011. Chalk: its stratigraphy, structure and engineering geology in east London and the Thames Gateway. *Quarterly Journal of Engineering Geology and Hydrogeology*, 44, 419-444.

NAGRA. 2002. NTB 02-05 Project Opalinus Clay Safety Report “Demonstration of Disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate level waste (Entsorgungsnachweis)” *NAGRA Technischer Bericht NTB 02-05 NAGRA, Wettingen Switzerland.*

Nirex, 2003. Generic Disposal System Specification. Nirex Report N/075.

Nirex, 2005. The Viability of a Phased Geological Repository Concept for the Long term Management of the UK’s Radioactive Waste. Nirex Report N/122.

Norry, M.J., Dunham, A.C. and Hudson, J.D. 1994. Mineralogy and geochemistry of the Peterborough Member, Oxford Clay Formation, Jurassic, UK: element fractionation during mudrock sedimentation. *Journal of the Geological Society, London*, 151, 195-207.

Northolt, A.J.G. and Highley, D.E. 1973. *Salt*. Mineral Dossier No. 7, Mineral Resources Consultative Committee, H.M.S.O., London, 36pp.

NDA. 2010. *Geosphere Status Report*. Nuclear Decommissioning Authority, 103pp.

Parker, R. 1992. Hot Dry Rock Geothermal Energy development in Cornwall (1974-1991). *Camborne School of Mines Journal* 1992, 22-31.

Plant, J.A., Jones, D.G. and Haslam, H.W. 1999. *The Cheshire Basin: Basin evolution, fluid movement and mineral resources in a Permo-Triassic rift setting*. Keyworth, Nottingham: British Geological Survey.

Roberts, B. And Merriman, R.J. 1985. The distinction between Caledonian burial and regional metamorphism in metapelites from North Wales: an analysis of isocryst patterns *Journal of the Geological Society of London*. 142, 615-624.

Robertson, S. 1999. BGS Rock Classification Scheme Volume 2: Classification of metamorphic rocks. *British Geological Survey Research Report*, RR/99/02. 24pp.

Robinson, D. and Bevins, R.E. 1986. Incipient metamorphism in the Lower Palaeozoic marginal basin of Wales. *Journal of Metamorphic Geology*, 4, 101-113.

Schulze, O., Popp, T. and Kern, H. 2001. Development of damage and permeability in deforming rock salt. *Engineering Geology*, 61, 163-180.

Seymour, K.J., Ingram, J.A. and Gebbett, S.J. 2006. Structural controls on groundwater flow in the Permo-Triassic sandstones of NW England. In: Barker, R.D., Tellam, J.H. (Eds.), *Fluid Flow and Solute Movement in Sandstones: the Onshore UK Permo-Triassic Red Bed Sequence*. *Geological Society, London*, 169–185.

Shand, P., Abesser, C., Farr, G., Wilton, N., Lapworth, D.J., Goody, D.C., Haria, A. and Hargreaves, R., 2005. Baseline Report Series 17: The Ordovician and Silurian metasedimentary aquifers of central and south-west Wales. *British Geological Survey Commissioned Report* CR/05/034N.

Shaw, R.P., Everett, P., Beamish, D., Chadwick, R.A., Kingdon, A., Marchant, A.P., Napier, B.J., Pharaoh, T.C., Powell, J.H., West, J.M. and Williams, G. 2011. Interpretation and

Modelling: Geology to support the development of an Integrated Site Descriptive Model. *British Geological Survey Open Report OR/11/057*.

Stow, D.A.V. 2009. *Sedimentary Rocks in the Field A Colour Guide*. Manson, London.

Strong, G.E., Milodowski, A.E., Pearce, J.M., Kemp, S.J., Prior, S.V. and Morton, A.C. 1994. The petrology and diagenesis of Permo-Triassic rocks of the Sellafield area, Cumbria. *Proceedings of the Yorkshire Geological Society*, 50, 77-89.

Taylor, G.K. 2007. Pluton shapes in the Cornubian Batholith: new perspectives from gravity modelling. *Journal of the Geological Society of London*. 164, 525-528.

Wahlgren, C.-H. 2010. *Oskarshamn site investigation. Bedrock geology –overview and excursion guide*. SKB Report R-10-05. 47pp.

Water Resources Board. 1972. *The hydrogeology of the London Basin*. Water Resources Board, London.

Watson, S., Metcalfe, R., Paulley, A., McEwan, T. and Michie, U. 2007. Identification of how aspects of NIREX PGRC would differ if adapted to alternative geologies, *Quintessa Report QRS-1338A-1*.