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National Geological Screening: Northern England region

Minerals and Waste Programme

Commissioned Report CR/17/103

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/103

National Geological Screening: Northern England region

C Waters[1], D Schofield[1], D E Evans[2], D Millward[2], R Haslam[2], B Ó'Dochartaigh[3], J P Bloomfield[3], J R Lee[4], B Baptie[4], R P Shaw[5], T Bide[5] and F M McEvoy

[1]Rock type, [2]Rock structure, [3]Groundwater, [4]Natural processes, [5]Resources

Contributors/editors

L P Field, R Terrington, P Williamson, I Mosca, N J P Smith, C Gent, M Barron, A Howard, G Baker, R M Lark, A Lacinska, S Thorpe, H Holbrook, I Longhurst, L Hannaford and J R Ford

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British Geological Survey offices

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales

Tel 0115 936 3241 Fax number removed
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP

Tel 0131 667 1000
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Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place, Cardiff CF10 3AT

Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB

Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House, Swindon SN2 1FL

Tel 01793 444000
www.ukri.org

Website www.bgs.ac.uk
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Foreword

This report is the published product of one of a series of studies covering England, Wales and Northern Ireland commissioned by Radioactive Waste Management (RWM) Ltd. The report provides geological information about the Northern England region to underpin the process of national geological screening set out in the UK's government White Paper *Implementing geological disposal: a framework for the long-term management of higher activity radioactive waste* (DECC, 2014). The report describes geological features relevant to the safety requirements of a geological disposal facility (GDF) for radioactive waste emplaced onshore and up to 20 km offshore at depths between 200 and 1000 m from surface. It is written for a technical audience but is intended to inform RWM in its discussions with communities interested in finding out about the potential for their area to host a GDF.

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Acronyms and abbreviations

BGS	British Geological Survey
BRITPITS	BGS database of mines and quarries
DECC	Department of Energy and Climate Change (now department for Business, Energy and Industrial Strategy (BEIS))
DTI	Detailed technical instruction and protocol
DTM	Digital terrain model
Fm	Formation
GDF	Geological disposal facility
GIS	Geographical information system
GSI3D	Geological surveying and investigation in 3D software
GVS	Generalised vertical section
HSR	Higher strength rock
IRP	Independent review panel
ka	1000 years before present
LEX	BGS Lexicon of named rock units
LSSR	Lower strength sedimentary rock
m bgl	Metres below ground level
Mb	Member
Ml	Local magnitude
Mw	Moment magnitude
NGS	National Geological Screening
NGS3D	Three dimensional geological model derived from UK3D for the national geological screening exercise
OD	Ordnance datum
PA	Principal aquifer
PRTI	Potential rock type of interest
RCS	BGS Rock Classification Scheme
RWM	Radioactive Waste Management Ltd
TIR	Technical information report
UK3D	UK three-dimensional geological model

Glossary

This glossary defines terms which have a specific meaning above and beyond that in common geoscientific usage, or are specific to this document.

Aquifer — a body of rock from which groundwater can be extracted. See also definition of principal aquifer.

Aquitard — a rock with limited permeability that allows some water to pass through it, but at a very reduced rate (Younger, 2017).

BGS Lexicon — the BGS database of named rock units and BGS definitions of terms that appear on BGS maps, models and in BGS publications. Available at http://www.bgs.ac.uk/lexicon/home.html

Depth range of interest — 200 to 1000 m below the NGS datum (see NGS datum definition).

Detailed technical instruction (DTI) — this sets out the methodology for producing the technical information reports and supporting maps.

Evaporites — rocks that formed when ancient seas and lakes evaporated. They commonly contain bodies of halite that provide a suitably dry environment and are weak and creep easily so that open cracks cannot be sustained (RWM, 2016a).

Generalised vertical section (GVS) — a table describing the lithostratigraphic units present within the region, displayed in their general order of superposition.

Geological attributes — characteristics of the geological environment relevant to the long-term safety requirements of a GDF. They may be characteristics of either the rock or the groundwater or may relate to geological processes or events (RWM, 2016a).

Geological disposal facility (GDF) — a highly engineered facility capable of isolating radioactive waste within multiple protective barriers, deep underground, to ensure that no harmful quantities of radioactivity ever reach the surface environment.

Higher strength rock (HSR) — higher strength rocks, 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 (RWM, 2016a).

Host rock — the rock in which a GDF could be sited.

Lower strength sedimentary rock (LSSR) — lower strength sedimentary rocks are fine-grained sedimentary rocks with a high content of clay minerals that provides their low permeability; they are mechanically weak, so that open fractures cannot be sustained (RWM, 2016a).

Major faults — faults with a vertical throw of at least 200 m and those that give rise to the juxtaposition of different rock types and/or changes in rock properties within fault zones, which may impact on the behaviour of groundwater at GDF depths (RWM, 2016b).

National geological screening (NGS) — as defined in the 2014 White Paper *Implementing Geological Disposal*, the national geological screening exercise will provide information to help answer questions about potential geological suitability for GDF development across the country. It will not select sites and it will not replace the statutory planning and regulatory processes that will continue to apply to a development of this nature.

NGS datum — an alternative datum for depth as described in the DTI, defined by a digital elevation model interpolated between natural courses of surface drainage in order to address a potential safety issue around GDF construction in areas of high topographical relief.

NGS3D — a screening-specific platform extracted from the BGS digital dataset, termed UK3D. In order to ensure the separation between the source material and the screening-specific platform, the extract has been saved, and is referred to as NGS3D.

Potential rock type of interest — a rock unit that has the potential to be a host rock and/or a rock unit in the surrounding geological environment that may contribute to the overall safety of a GDF.

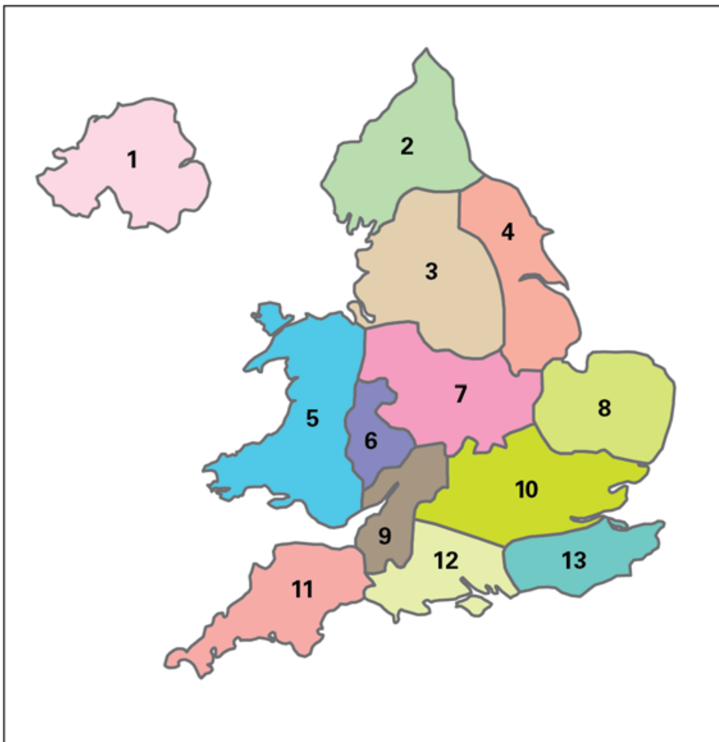
Principal aquifer — a regionally important aquifer defined by the Environment Agency as layers of rock that have high intergranular and/or fracture permeability, meaning they usually provide a high level of water storage (Environment Agency, 2013).

The guidance — national geological screening guidance as set out by RWM, which identifies five geological topics relevant to meeting the safety requirements for a geological disposal facility.

UK3D — a national-scale geological model of the UK consisting of a network, or 'fence diagram', of interconnected cross-sections showing the stratigraphy and structure of the bedrock to depths of 1.5 to 6 km. UK3D v2015 is one of the principal sources of existing information used by the national geological screening exercise (Waters et al., 2015).

1 Introduction

The British Geological Survey (BGS) was commissioned by Radioactive Waste Management Ltd (RWM) to provide geological information to underpin its process of national geological screening set out in the United Kingdom (UK) Government's White Paper *Implementing geological disposal: a framework for the long-term management of higher activity radioactive waste* (DECC, 2014). The geological information is presented in a series of reports, one for each of 13 regions of England, Wales and Northern Ireland (Figure 1) that describe the geological features relevant to the safety requirements of a geological disposal facility (GDF) for radioactive waste emplaced onshore and up to 20 km offshore at depths between 200 and 1000 m from surface. The production of these reports followed a methodology, termed detailed technical instructions (DTI), developed by the BGS in collaboration with RWM safety case experts, and evaluated by an independent review panel (RWM, 2016b). They are written for a technical audience but are intended to inform RWM in its discussions with communities interested in finding out about the potential for their area to host a GDF. This report contains an account of the Northern England region (Figure 1).



1	Northern Ireland
2	Northern England
3	Pennines and adjacent areas
4	Eastern England
5	Wales
6	Welsh Borderland
7	Central England
8	East Anglia
9	Bristol and Gloucester region
10	London and the Thames valley
11	South-west England
12	Hampshire Basin and adjoining areas
13	Wealden district

Figure 1 The BGS region boundaries as defined by the Regional Guides series of reports (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html). British Geological Survey © UKRI 2018.

2 Background

2.1 NATIONAL GEOLOGICAL SCREENING GUIDANCE

The approach adopted by RWM follows instruction laid out in a White Paper *Implementing geological disposal: a framework for the long-term management of higher activity radioactive waste* (DECC, 2014) to undertake a process of 'national geological screening' based on 'existing generic GDF safety cases' using publicly available data and information (Figure 2). To satisfy these requirements, RWM developed a national geological screening 'guidance' paper (RWM, 2016a) that describes:

- safety requirements to which the 'geological environment' contributes
- geological 'attributes' that are relevant to meeting these safety requirements
- sources of existing geological information that allow the geological attributes to be understood and assessed
- the outputs (documents and maps) that will be produced as part of the 'screening' exercise

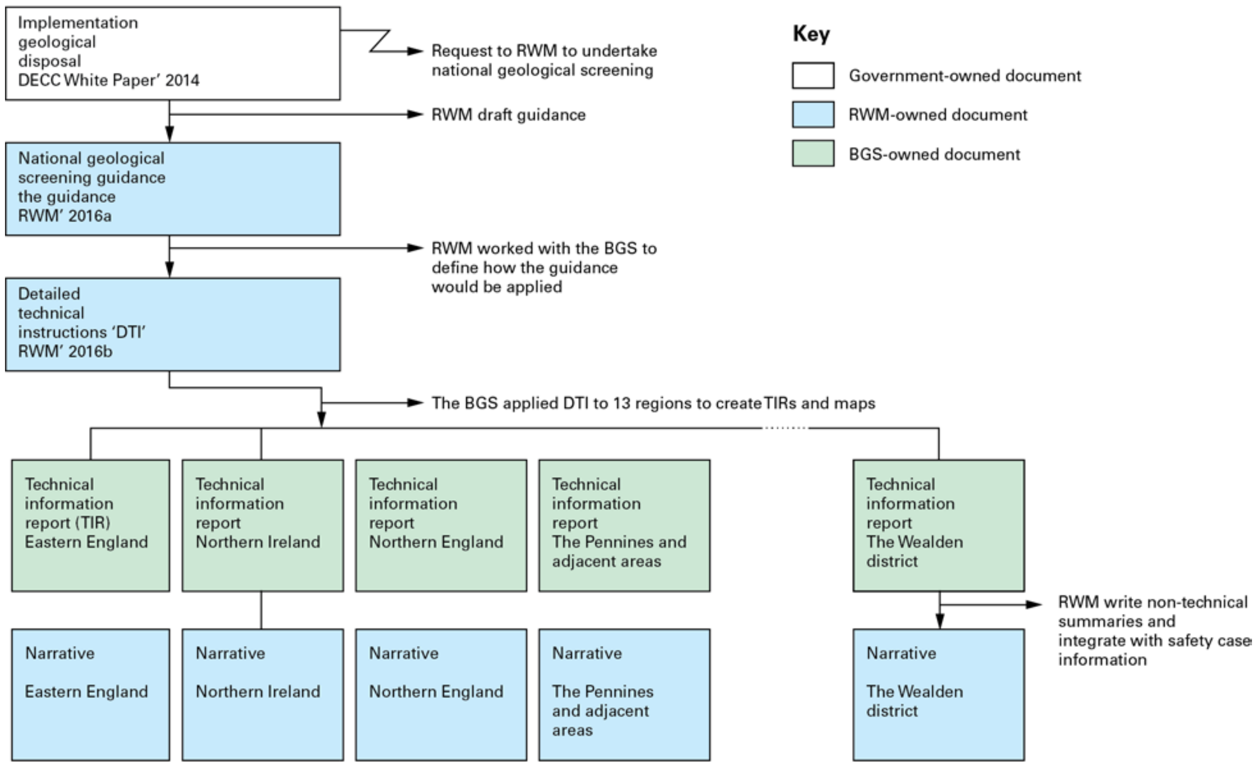


Figure 2 Schematic diagram of the national geological screening process and arising documents.

The geological attributes identified by RWM that at are relevant to the safety case of a GDF fall into five topic areas: rock type, rock structure, groundwater, natural processes and resources, as described in Table 1.

Table 1 Geological topics and attributes relevant to safety requirements as set out in the national geological screening guidance (RWM, 2016a).

Geological topic	Geological attributes
Rock type	Distribution of potential host rock types (higher strength rocks, lower strength sedimentary rocks, evaporite rocks) at the depths of a GDF
	Properties of rock formations that surround the host rocks
Rock structure	Locations of highly folded zones
	Locations of major faults
Groundwater	Presence of aquifers
	Presence of geological features and rock types that may indicate separation of shallow and deep groundwater systems
	Locations of features likely to permit rapid flow of deep groundwater to near-surface environments
	Groundwater age and chemical composition
Natural processes	Distribution and patterns of seismicity
	Extent of past glaciations
Resources	Locations of existing deep mines
	Locations of intensely deep-drilled areas
	Potential for future exploration or exploitation of resources

2.2 DETAILED TECHNICAL INSTRUCTIONS

In order to gather and present the appropriate geological information in a systematic and consistent way across the 13 regions of England, Wales and Northern Ireland, RWM worked with the BGS to develop appropriate methodologies to provide the information on the geological attributes relevant to safety requirements set out in the guidance paper (RWM, 2016a) for each of the five geological topics (Table 1). These instructions are referred to as detailed technical instructions (DTIs) (Figure 2). In developing the DTIs, the BGS provided geoscientific expertise whilst RWM contributed safety-case expertise.

The DTIs were intended to provide the BGS with an appropriate technical methodology for the production of the technical information reports (TIRs) (Figure 2) and maps, but which retained an element of flexibility to take account of variations in data availability and quality. The DTIs are specific to each of the five geological topics: rock type, rock structure, groundwater, natural processes and resources. For each, the DTI sets out a step-by-step description of how to produce each output, including how the data and information related to the topic will be assembled and presented to produce the TIRs and any associated maps required by the guidance. Specifically, for each topic, the DTI describes:

- the definitions and assumptions (including use of expert judgements) used to specify how the maps and TIRs are produced
- the data and information sources to be used in producing the maps and TIRs for the study
- the process and workflow for the analysis and interpretation of the data and for the preparation of a description of the required outputs of maps and the text components of the TIRs.

The reader is referred to the DTI document (RWM, 2016b) for further details of how the TIR and maps are produced for each of the five geological topics.

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

The TIRs, of which this report is one, describe those aspects of the geology of a region onshore and extending 20 km offshore at depths between 200 and 1000 m below NGS datum of relevance to the safety of a GDF. Due to their technical nature, TIRs are intended for users with specialist geological knowledge.

Each TIR addresses specific questions posed in the guidance (Table 1) and does not therefore provide a comprehensive description of the geology of the region; rather they describe the key characteristics of the geological environment relevant to the safety of a GDF. For each geological topic the following aspects are included.

i. Rock type

- an overview of the geology of the region including a generalised geological map and illustrative cross-sections
- an account of the potential rock types of interest (rock units with the potential to be host rocks and/or rocks in the surrounding environment that may contribute to the overall safety of a GDF that occurs between 200 and 1000 m below NGS datum in the region, classified by the three host rock types (see glossary)
- for each potential rock type of interest, a description of its lithology, spatial extent and the principal information sources

ii. Rock structure

- a description of the major faults in the region with a map showing their spatial distribution
- a description of areas of folded rocks with complex properties and their location shown on a map

iii. Groundwater

- an explanation of what is known of shallow and deep groundwater flow regimes, of the regional groundwater flow systems, and of any units or structures that may lead to the effective separation of deep and shallow groundwater systems, including evidence based on groundwater chemistry, salinity and age
- a description of the hydrogeology of the potential rock types of interest, the principal aquifers (see glossary) and other features, such as rock structure or anthropogenic features (including boreholes and mines), that may influence groundwater movement and interactions between deep and shallow groundwater systems
- a note on the presence or absence of thermal springs (where groundwater is >15º C), which may indicate links between deep and shallow groundwater systems

iv. Natural processes

- an overview of the context of the natural processes considered, including glaciation, permafrost and seismicity
- a national map showing the extent of past glaciation
- a national map showing the distribution of recent seismicity
- a national-scale evaluation of glacial, permafrost and seismic processes that may affect rocks at depths between 200 and 1000 m below NGS datum
- an interpretation of the natural processes pertinent to the region in the context of available national information (on seismicity, uplift rate, erosion rate and past ice cover during glaciations)

v. Resources

- for a range of commodities, an overview of the past history of deep exploration and exploitation with a discussion of the potential for future exploitation of resources
- regional maps showing historic and contemporary exploitation of metal ores, industrial minerals, coal and hydrocarbons at depths exceeding 100 m
- a description of the number and distribution of boreholes drilled to greater than 200 m depth in the region, accompanied by a map displaying borehole density (i.e. the number of boreholes per km^2)

3 The Northern England region

This region covers the area of Northern England extending from the Scottish border southwards to Morecambe Bay in the west and Teesside in the east, covering the counties of Cumbria, Durham, Tyne and Wear and Northumberland and northern parts of Cleveland, Yorkshire and Lancashire. The region’s diverse landscape reflects the underlying bedrock geology summarised in Figures 3 and 4. The mainly lowland parts of west, north and east Cumbria, Tyne and Wear and County Durham show a mudstone-dominated succession ranging from Triassic to Early Jurassic age. These pass down into a sandstone-dominated succession of Permo-Triassic age that is a major aquifer in the region. Underlying Permian strata are dominated by sandstones and mudstones in the west of the region and limestones and mudstones in the east, both areas associated with halites. Parts of south and east Cumbria are underlain by Carboniferous limestones, but much of the uplands of the Pennines are defined by Carboniferous sandstones and mudstones. Industrial and urban developments around Whitehaven and Workington in west Cumbria and Newcastle upon Tyne to Durham in the east of the region are centred near accumulations of natural mineral resources including coal. The Lake District comprises a mountainous area underlain by sedimentary and igneous rocks of Ordovician and Silurian age, whereas the Cheviot Hills are mainly underlain by sedimentary and igneous rocks of Silurian and Devonian age.

The geology of the region is well known at and near the surface from natural exposures of rocks along rivers, crags and coastal cliffs, together with observations in quarries and opencast pits and mine workings. Below about 50 m most information comes from boreholes drilled for water, coal or for minerals but these are mainly confined to areas where economic resources have been exploited. There are relatively few boreholes deeper than 250 m, mainly for hydrocarbons exploration. These occur in areas where understanding of the deep subsurface has also been improved by interpretation of geophysical seismic surveys. Seismic survey data is particularly important for interpretation of the geology in the Solway Lowlands and eastwards into Northumberland. Other regional-scale geophysical surveys reveal patterns of the Earth’s gravity and magnetic field which have been used to detect and infer the deep geological structure beneath the Lake District, the north Pennines and the Cheviot Hills (Figure 4).

3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

The geology at surface in the region is shown in Figure 3 and Figure 4 illustrate the geological variation across the region. The reader is referred to the regional summary on the BGS website (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html) for a non-technical overview of the geology of the region and to national geological screening: Appendix A (Pharaoh and Haslam, 2018) for an account of the formation and structure of the basement, and the older and younger cover rocks of the UK.

Geologically, the region can be broadly subdivided into a series of depositional basins, typically associated with thicker and more complete successions, and blocks in which thinner and less complete sedimentary successions predominate. Key basins within the region are: the East Irish Sea and Solway Firth basins, located offshore of the Cumbria coast and with a basin fill of Permo-Triassic rocks; the Carlisle basin, located onshore in north Cumbria extending southwards into the Vale of Eden basin, also associated with deposition of Permo-Triassic rocks; the Cleveland basin, present in the south of the region and affecting Permo-Triassic and Carboniferous strata; the Solway–Northumberland basin, extending across the northern parts of the region; the Tweed basin in north-east Northumberland, and the Stainmore basin of the extreme south of the region, all affecting Carboniferous strata. The main structural blocks include the Alston block, located in the north Pennines, influencing Carboniferous and older strata, and the Lake District and Cheviot blocks, dominated by Ordovician to Devonian sedimentary and igneous rocks. All three blocks are underlain by extensive granite plutons (Figure 4), although in the Alston block these igneous intrusive rocks are only present at depth.

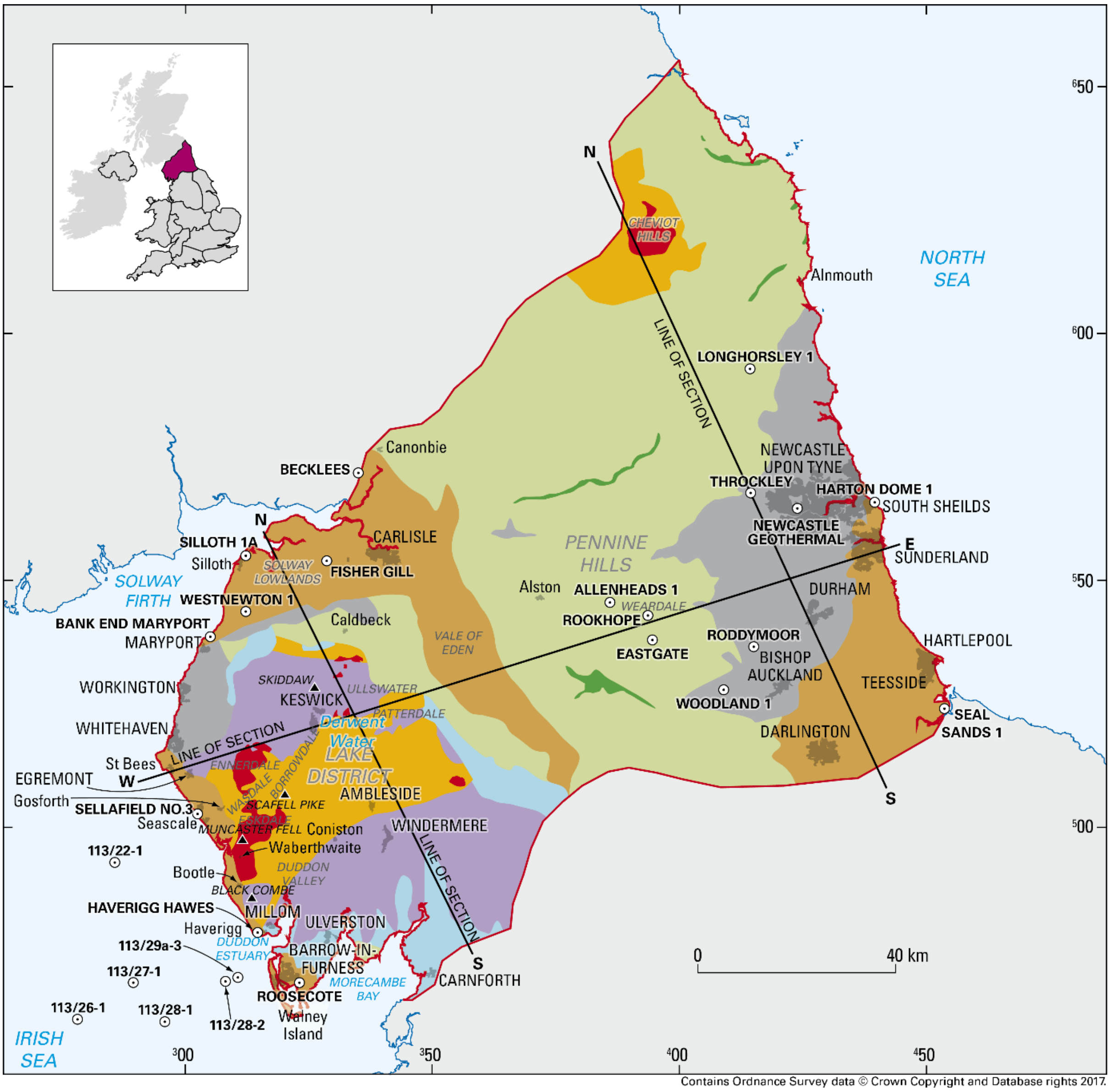

NORTH SEA
IRISH SEA
SOLWAY FIRTH
CHEVIOT HILLS
Alnmouth
LONGHORSLEY 1
LINE OF SECTION
NEWCASTLE UPON TYNE
THROCKLEY
HARTON DOME 1
SOUTH SHEILDS
NEWCASTLE GEOTHERMAL
SUNDERLAND
DURHAM
PENNINE HILLS
Alston
ALLENHEADS 1
WEARDALE
ROOKHOPE
EASTGATE
RODDYMOOR
BISHOP AUCKLAND
WOODLAND 1
HARTLEPOOL
TEESSIDE
SEAL SANDS 1
DARLINGTON
Canonbie
BECKLEES
CARLISLE
SILLOTH 1A
Silloth
SOLWAY LOWLANDS
FISHER GILL
WESTNEWTON 1
BANK END MARYPORT
MARYPORT
Caldbeck
VALE OF EDEN
WORKINGTON
SKIDDAW
KESWICK
ULLSWATER
PATTERDALE
Derwent Water
WHITEHAVEN
LAKE DISTRICT
St Bees
EGREMONT
Gosforth
ENNERDALE
BORROWDALE
WASDALE
ESKDALE
SCAFELL PIKE
AMBLESIDE
SELLAFIELD NO.3
Seascale
MUNCASTER FELL
Coniston
WINDERMERE
Waberthwaite
113/22-1
Bootle
DUDDON VALLEY
BLACK COMBE
HAVERIGG HAWES
MILLOM
ULVERSTON
Haverigg
DUDDON ESTUARY
113/29a-3
BARROW-IN-FURNESS
113/27-1
MORECAMBE BAY
ROOSECOTE
CARNFORTH
113/26-1
113/28-1
113/28-2
Walney Island
N
S
W
E
0
40 km
650
600
550
500
300
350
400
450
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Figure 3 Generalised geological map and key showing the distribution of younger sedimentary rocks, older sedimentary and igneous rocks and basement rocks in the onshore Northern England region. The inset map shows the extent of the region in the UK. See Figure 4 for schematic cross-sections. The ‘Geological sub units’ column is highly generalised and does not represent all geological units in the region. Stratigraphical nomenclature and lithological descriptions are simplified and may differ from those used in other sections of this report. The locations of key boreholes mentioned in the text are shown by a circle and dot. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

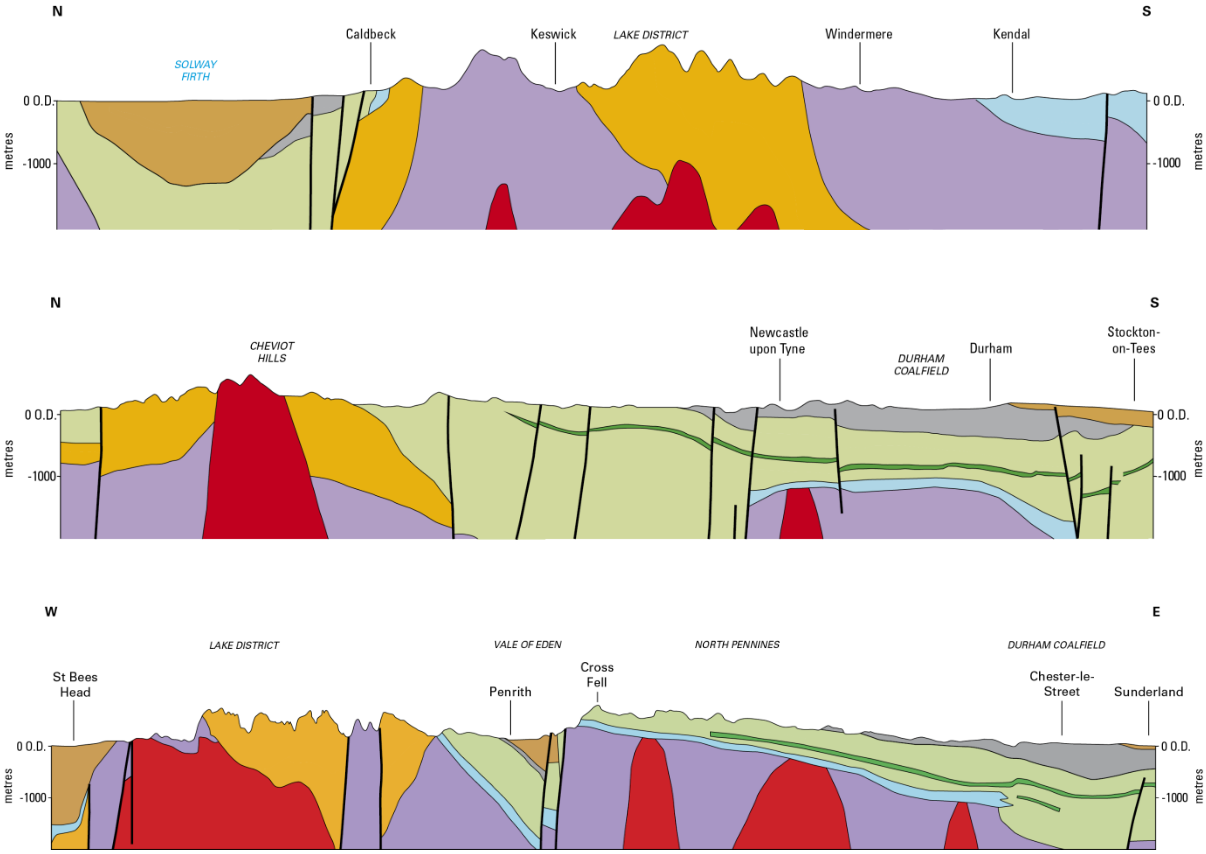

Figure 4 Schematic cross-sections through the Northern England region. Top: north–south section through the Lake District; centre: north–south section through the Cheviot Hills and the Durham and Northumberland coalfield; bottom: west–east section through the Lake District, north Pennines and the Durham and Northumberland coalfield. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

4 Screening topic 1: rock type

4.1 OVERVIEW OF ROCK TYPE APPROACH

The rock type DTI (RWM, 2016b) sets out how data and information on the topic of rock type are assembled and presented to produce maps for each region showing the ‘distribution of potential host rocks at 200 to 1000 m depth’ and ‘rock formations that surround the host rocks’. For this study, these are combined and referred to as ‘potential rock types of interest’ (PRTIs). Therefore, PRTIs are defined as rock units that have the potential to be host rocks and/or rocks in the surrounding geological environment that may contribute to the overall safety of a GDF. An example of the latter is a mudstone that may be insufficient in thickness to host a GDF but could potentially act as a barrier to fluid flow above the host rock.

The methodology for selecting units as PRTIs is described in the DTI document (RWM, 2016b) and is summarised here. Guided by the safety requirements for a GDF, in the form of selection criteria, lithologies were assigned to each of the generic host rock types as shown in Table 2.

Table 2 Lithologies assigned to each of the generic host rock types. *Definitions of the generic host rock types are provided in the glossary.

Generic host rock type	**Selection criteria (where available)**	**Lithologies to be considered PRTIs**
Evaporite*	• halite	Rock-salt
Lower strength sedimentary rocks*	• high clay content (low permeability) • continuous laterally on a scale of tens of kilometres • no minimum thickness • mechanically weak (not metamorphosed)	Clay
		Mudstone
Higher strength rocks*	• low matrix porosity • low permeability • homogeneous bodies on a scale to accommodate a GDF • 80% of the mapped unit must be made up of the specific PRTI	Older compacted and metamorphosed mudstones of sedimentary or volcanic origin within established cleavage belts
		Extrusive igneous rock
		Intrusive igneous rock such as granite
		Metamorphic rock — medium to high grade

The lithologies were extracted from the NGS3D model, a three-dimensional geological model derived from the UK3D v2015 model (Waters et al., 2015) comprising a national network, or ‘fence diagram’, of cross-sections that show the bedrock geology to depths of at least 1 km. The stratigraphical resolution of the rock succession is based on the UK 1:625 000 scale bedrock geology maps (released in 2007) and has been adapted for parts of the succession by further subdivision, by the use of geological age descriptions (i.e. chronostratigraphy rather than lithostratigraphy), and to accommodate updates to stratigraphical subdivisions and nomenclature. Lithostratigraphical units are generally shown at group-level (e.g. Lias Group), or subdivided to formation-level (e.g. Burnham Chalk Formation). Amalgamations of formations are used to accommodate regional nomenclature changes or where depiction of individual formations would be inappropriate at the scale of the model (e.g. Kellaways Formation and Oxford Clay Formation (Undivided)). Chronostratigraphical units are classified according to their age and lithology (e.g. Dinantian rocks – limestone; Silurian rocks (undivided) – mudstone, siltstone and sandstone). Igneous rocks are generally classified based on formation, age and lithology (e.g. Unnamed extrusive rocks, Silurian to Devonian - mafic lava and mafic tuff).

The NGS3D (see glossary) was developed from UK3D v2015 including the incorporation of additional stratigraphical detail to allow the modelling of halite units. The NGS3D model was used as an information source for estimating the presence, thickness, depth of occurrence of geological units discussed below, and the geometry of their boundaries. Interpretations based on this model rely on geological relationships depicted in cross-sections, and it is possible that understanding of these relationships in some areas may be limited by cross-section data availability.

The units extracted from the NGS3D model, the PRTIs (see RWM, 2016b for a description of the methodology), were used as the basis for writing the rock type section of this document. For each PRTI, an overview of its distribution, lithology and thickness is given, including information on the variability of these properties, if available, along with references to key data from which the information is derived. Information on the distribution of each PRTI between 200 and 1000 m is guided by the geological sections in the NGS3D model.

4.2 POTENTIAL ROCK TYPES OF INTEREST IN THE NORTHERN ENGLAND REGION

For the Northern England region, the GVS groups the rocks into three age ranges: younger sedimentary rocks (Jurassic, Triassic and Permian), older sedimentary and igneous intrusive rocks (Carboniferous to Permian) and basement rocks (Devonian and older) (Table 3). Some of the rock units are considered to represent PRTIs present within the depth range of interest, between 200 and 1000 m below NGS datum. These include a number of lower strength sedimentary rock units (LSSR) and evaporite (EVAP) PRTIs in the younger and older sedimentary rocks as well as higher strength rock (HSR) PRTIs in the older sedimentary and igneous intrusive rocks as well as basement rocks.

The Early Jurassic Lias Group, a potential LSSR, is present at outcrop in a continuous but small outlier centred on Great Orton, west of Carlisle, north Cumbria (Figure 4). It is not considered to extend to depths suitable for this to be a PRTI in this region and hence is not discussed further.

Those mudstone-dominated successions that are considered HSRs have all been subject to varying degrees of deformation and low-grade metamorphism (epizone and anchizone) during the Acadian Orogeny, and have a pervasive slaty cleavage. The extent of the cleaved facies becomes less certain eastwards and therefore mudstone-dominated successions to the east of are Lake District are not considered to have a pervasive cleavage are not included as a HSR and are not discussed further. Undivided early Palaeozoic rocks (within NGS3D) are a potential HSR inferred to be present beneath Carboniferous strata within the Solway–Northumberland basin and in the East Irish Sea basin, but in both cases deeper than the depth range of interest and are also not discussed further.

The PRTIs are described in Table 3 in stratigraphical order from youngest to oldest (i.e. in downward succession), grouped by the three age ranges: younger sedimentary rocks, older sedimentary rocks and basement rocks. The descriptions include the distribution of the PRTI at surface (outcrop) and where the PRTI is present below the surface (subcrop) within the depth range of interest, along with key evidence for the interpretations. The main geological properties of the PRTIs and how these vary across the region are also summarised. Data are mostly taken from the Regional Guide to Northern England (Stone et al., 2010) and other published sources (see references). They may include terminology or nomenclature that has been updated since those publications were released. The term ‘mudstone’ follows BGS usage to include claystone and siltstone-grade siliciclastics (Hallsworth and Knox, 1999). The location of boreholes referred to in this chapter is shown on Figure 3.

The NGS3D model (see glossary) was used as an information source for estimating the presence, thickness, depth of occurrence of geological units discussed below, and the geometry of their boundaries. Interpretations based on this model rely on borehole-derived geological relationships depicted in cross-sections, and it is possible that understanding of these relationships in some areas may be limited by cross-section data availability.

Three maps showing the generalised lateral distribution of PRTIs between 200 and 1000 m below NGS datum for the three generic host rock types are provided in Figures 5, 6 and 7. A summary map showing the generalised combined lateral distribution of all PRTIs is provided in Figure 8.

Table 3 Schematic GVS for the Northern England region showing units that contain PRTIs and/or principal aquifers. Geological units are generally shown in stratigraphical order and display variable levels of resolution reflecting the resolution within the UK3D model. The units are not to vertical scale and due to regional variations; some units may be locally absent or may be recognised in different stratigraphical positions from those shown. See Figures 5, 6 and 7 for the regional distribution of PRTIs amalgamated by host rock model (i.e. LSSR, EVAP and HSR respectively).

Geological period		Geological unit identified in NGS3D	Dominant rock type	Potential rock types of interest			Principal aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS	Jurassic	Lias Group	Mudstone, siltstone, limestone and sandstone	N/A	N/A	N/A	N/A
	Triassic	Mercia Mudstone Group (including Penarth Group)	Mudstone with local siltstone and evaporite deposits of anhydrite, gypsum and halite	N/A	Mercia Mudstone Group and Penarth Group	Preesall Halite Mb/Fm; Mythop Halite, Rossall Halite and Fylde Halite members	N/A
		Sherwood Sandstone Group	Red sandstones, siltstones and mudstones	N/A	N/A	N/A	Sherwood Sandstone Group sandstones
	Permian	Cumbrian Coast Group (west of Pennines)	Mudstone, siltstone and sandstone with evaporites including halite	N/A	Eden Shales, St Bees Shale and Barrowmouth Mudstone formations	St Bees Evaporite Formation	N/A
		Permian rocks (undivided offshore only) (west of Pennines)	Mudstone, siltstone, sandstone, conglomerate and halite	N/A	Permian rocks (undivided)	Permian rocks (undivided)	N/A
		Appleby Group (west of Pennines)	Sandstone and conglomerate	N/A	N/A	N/A	Appleby Group sandstones
		Zechstein Group (east of Pennines)	Dolomitised limestone, dolostone and mudstone with varied evaporites	N/A	N/A	Fordon Evaporite Formation	Zechstein Group limestones and dolomitic limstones
		Rotliegendes Group (east of Pennines) — combined with Permian rocks (undivided) in NGS3D	Sandstone, breccia and conglomerate	N/A	N/A	N/A	Rotliegendes Group
OLDER SEDIMENTARY AND IGNEOUS ROCKS	Carboniferous to Permian	Warwickshire Group	Siltstone and sandstone with subordinate mudstone; siltstone, sandstone and mudstone with coal	N/A	Eskbank Wood Formation	N/A	N/A
		Unnamed igneous intrusion, Carboniferous to Permian	Dolerite and basalt	Whin Sill	N/A	N/A	N/A
	Carboniferous	Pennine Coal Measures Group	Mudstone, siltstone, sandstone, coal and ironstone	N/A	N/A	N/A	N/A
		Yoredale Group	Limestone, sandstone, siltstone, mudstone, limestone with subordinate sandstone and argillaceous rocks	N/A	N/A	N/A	N/A
		Millstone Grit Group	Sandstone, siltstone and mudstone	N/A	N/A	N/A	N/A
		Craven Group	Interbedded mudstone and limestone	N/A	N/A	N/A	N/A
		Border Group	Sandstone with subordinate argillaceous rocks and limestone	N/A	N/A	N/A	Fell Sandstone Formation
		Inverclyde Group	Sandstone, siltstone and mudstone with conglomerate, limestone, anhydrite and basalt	Cottonshope Volcanic, Kelso Volcanic and Birrenswark Volcanic formations	N/A	N/A	N/A
BASEMENT ROCKS	Ordovician to Devonian	Tournaisian–Visean rocks = Carboniferous Limestone Supergroup	Limestone, locally with mudstone, sandstones and conglomerate; volcanics	N/A	N/A	N/A	N/A
		Unnamed extrusive rocks, Silurian to Devonian	Andesite lava and tuff	Cheviot Volcanic Formation (Reston Group)	N/A	N/A	N/A
		Silurian rocks (undivided) = part Windermere Supergroup	Mudstone with siltstone, sandstone, limestone and rhyolites	Mudstone within the Stockdale Group; Tranearth and Kendal groups	N/A	N/A	N/A

		Ashgill rocks (undivided) = part Windermere Supergroup	Mudstone with siltstone, sandstone, limestone and rhyolites	Drygill mudstone and Dufton Mudstone formations; various rhyolitic ignimbrites and tuffs	N/A	N/A	N/A
		Riccarton Group	Sandstone, siltstone and silty mudstone	N/A	N/A	N/A	N/A
		Unnamed igneous intrusion, Ordovician to Silurian — felsic	Granite	Threlkeld microgranite	N/A	N/A	N/A
		Unnamed igneous intrusion, Ordovician to Silurian — mafic	Gabbro, dolerite and granophyre	Carrock Fell centre (Mosedale gabbro, Carrock granophyre)	N/A	N/A	N/A
		Ordovician volcanic rocks and sills	Basalt, andesite and dacite lavas and tuffs	Borrowdale Volcanic Group Eycott Volcanic Group	N/A	N/A	N/A
		Ordovician rocks (undivided)	Slaty mudstone, siltstone and sandstone	Skiddaw Group	N/A	N/A	N/A
		Intrusive igneous rocks	Granite, foliated	Lake District and north Pennine batholiths and Cheviot pluton	N/A	N/A	N/A

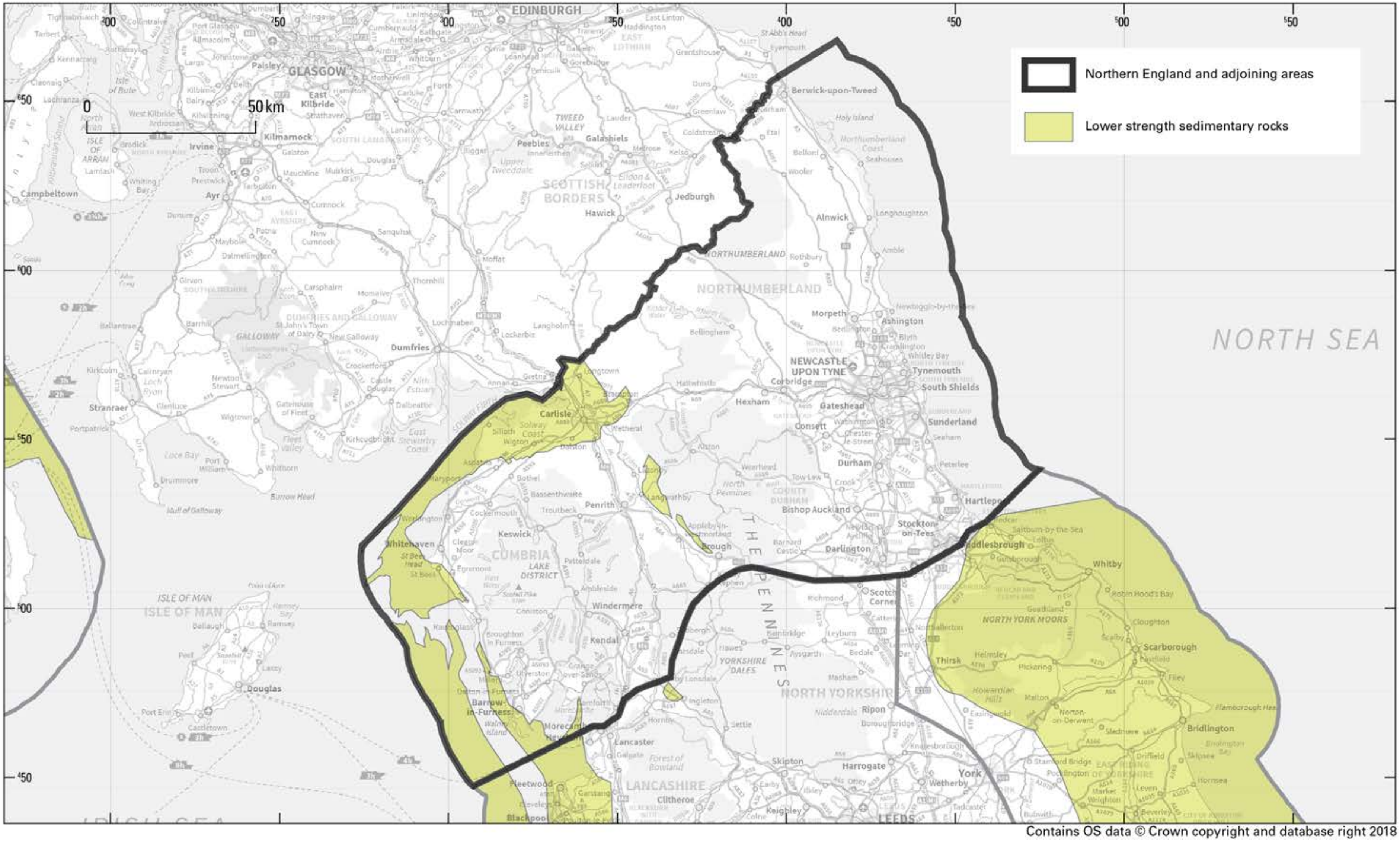

Figure 5 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Northern England region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

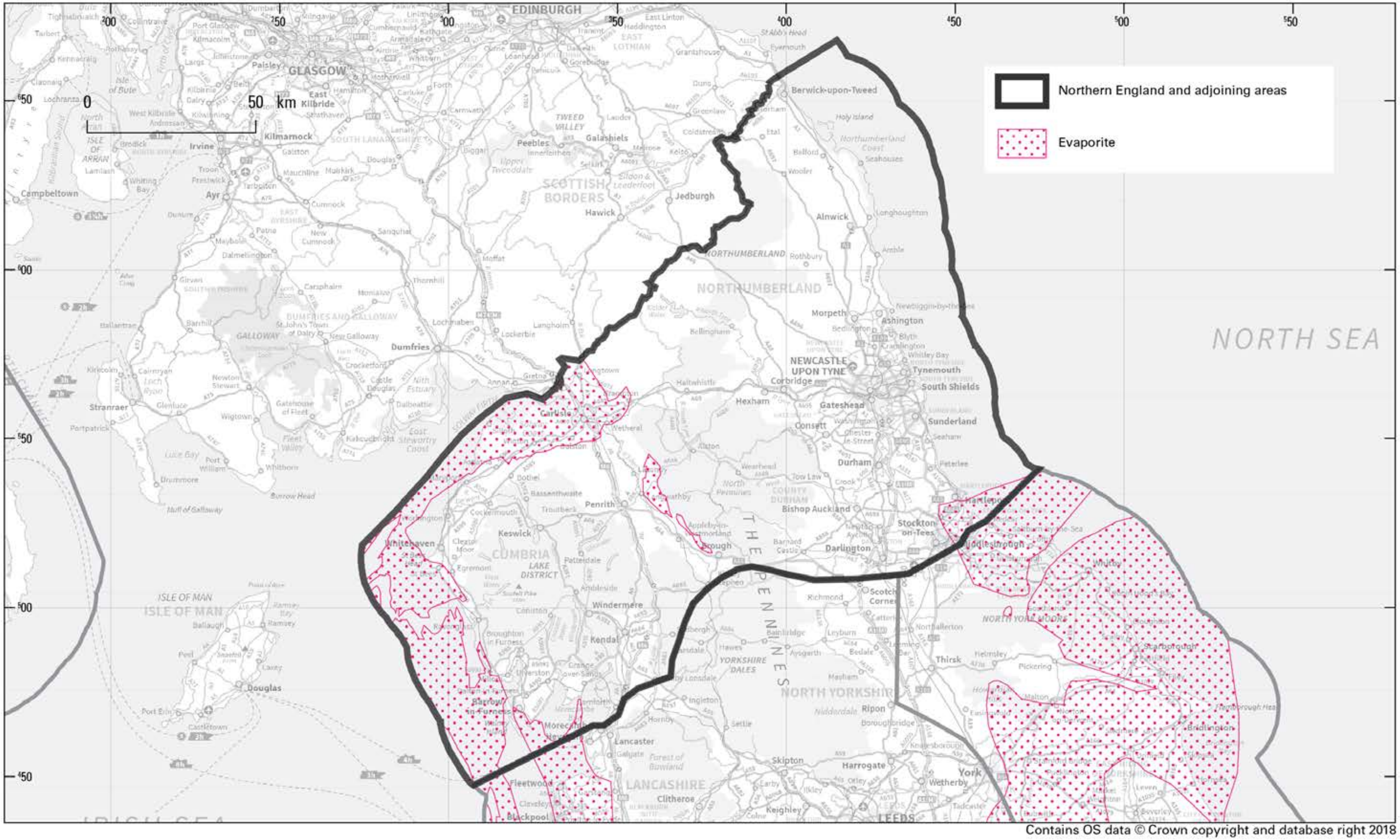

Figure 6 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the Northern England region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

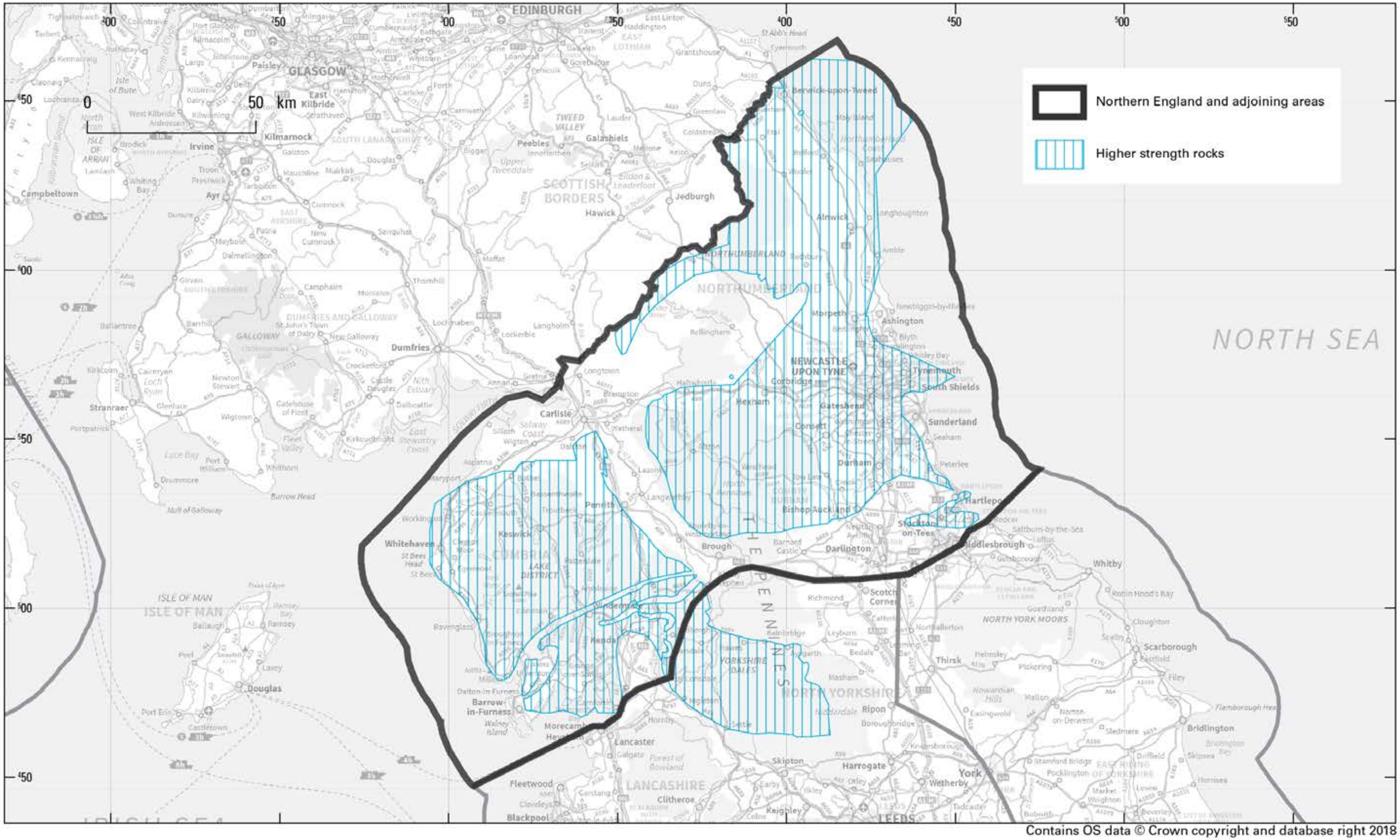

Figure 7 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Northern England region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

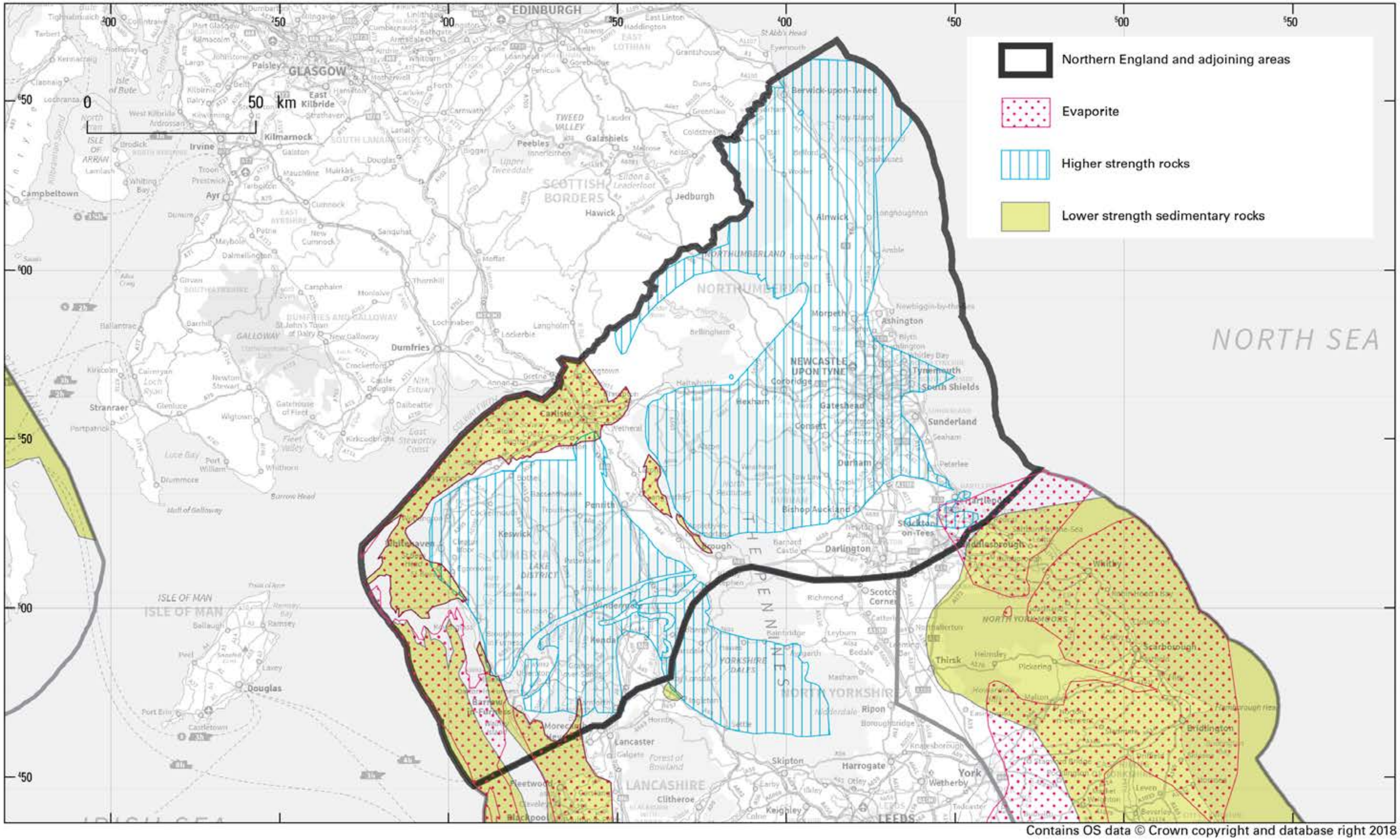

Figure 8 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Northern England region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

4.2.1 Younger sedimentary rocks

4.2.1.1 Mercia Mudstone Group and Penarth Group (Undivided) — LSSR and EVAP

The Mid to Late Triassic Mercia Mudstone Group is modelled undivided in NGS3D from the overlying, thinner Penarth Group. Both units occur at outcrop onshore in the Solway lowland plain west of Carlisle, with only the Mercia Mudstone Group extending to the depth range of interest. The succession is poorly exposed here, largely obscured by superficial deposits (Stone et al., 2010). In this area the Mercia Mudstone Group (formerly known as the Stanwix Shales) has insufficient information to allow the group to be subdivided into component formations and there is no information to suggest that thick halites (rock-salt) are present. The Penarth Group, which has not been mapped as a separate unit in this area, is about 13 m thick (Ivimey-Cook et al., 1995).

The two groups are not found onshore in west Cumbria, but the Mercia Mudstone Group is present close offshore within the depth range of interest as little as 2 km south-west of Seascale, with the faulted succession broadly deepening to the west but remaining within the depth range of interest for some 20 km offshore into the East Irish Sea (Figure 4). There, five main halite units are recorded within the Mercia Mudstone Group in deep boreholes and mapped using 2D seismic data (Jackson and Johnson, 1996) (Figure 9). In descending order, the halites are: the Warton Halite (0−269 m thick) and Preesall Halite (about 100−600 m) formations, and the Mythop Halite (51−249 m), Rossall Halite (0−148 m) and Fylde Halite (0−182 m) members (Jackson and Johnson, 1996). Both the Mercia Mudstone Group and the halite units within it become thinner and more condensed towards the coast (Jackson and Johnson, 1996), although Barnes et al. (2006) prefers an alternative interpretation where the thinning is a product of post-depositional erosion of the upper part of the group. All of these halites, with the exception of the Warton Halite Formation, occur within the depth range of interest about 20 km west of the coast at Seascale, but shallow rapidly to the east with the lower halites occurring more extensively (Figure 9).

In south Cumbria the Mercia Mudstone Group is present at crop beneath superficial deposits in Walney Island, Barrow-in-Furness, and extending offshore westwards in the depth range of interest some 5 km west of Walney Island, with the faulted succession broadly deepening to the west but within the depth range of interest some 20 km offshore (Figure 4). Evaporite rocks, principally gypsum, anhydrite and halite, occur within the lower part of the Mercia Mudstone Group and locally, in south Cumbria, the halite is excess of 100 m thick. About 20 km west of Walney Island, the Rossall Halite and Mythop Halite members and the Preesall Halite Member (equivalent to the Preesall Halite Formation in the offshore) locally occur within the depth range of interest, the Fylde Halite Member typically being too deep and the Warton Halite Formation too shallow. The Mercia Mudstone Group is underlain by the Sherwood Sandstone Group, and locally, west of Carlisle, the Penarth Group is overlain by the Lias Group.

Principal information sources

In the lowland Solway plain, west of Carlisle, seismic reflection data suggest the Mercia Mudstone Group is 200 to 250 m thick beneath the Penarth and Lias groups (Holliday et al., 2004), although in the Fisher Gill Borehole (Figure 3) the Mercia Mudstone Group is some 355 m thick. Holliday et al. (2004) considers that the Mercia Mudstone Group thickens westwards towards the north-west Cumbria coastline with 325 m proved beneath superficial deposits in the Silloth 1A Borehole. The base of the group is modelled in NGS3D to typical depths of 250–350 m below NGS datum, extending to depths of 550 m within the central part of the basin and shallowing to above the depth range of interest towards the east and south. The group is also modelled in the NGS model to extend into the offshore Solway Firth to depths of 570 m below NGS datum south of the Solway Firth fault system.

The Mercia Mudstone Group is inferred from seismic reflection data to be present offshore of the west Cumbria coast. The contours for the base of the Group (Evans et al., 1994; Nirex, 1995) display a faulted succession that broadly deepens to the west ranging from shallow depths offshore of Seascale to 1100 m below NGS datum some 20 km offshore of Millom. Much of the information concerning the succession, including the presence of five main halite units, comes from deep borehole information and interpretation of 2D seismic data from farther offshore by Jackson and Johnson (1996), which also provides maps showing the inferred distribution of the halites (Figure 9). The offshore hydrocarbons Borehole 113/22-1 proves the Mercia Mudstone Group from 154.53 to 956.46 m depth, with the bases of the Preesall Halite Formation (49.67 m proved beneath superficial deposits) at 162.14 m, the Mythop Halite Member (249.9 m thick) at

592.24 m, the Rossall Halite Member (74.7 m thick) at 829.04 m and Fylde Halite Member (42.3 m thick) at 907.04 m, below OS datum.

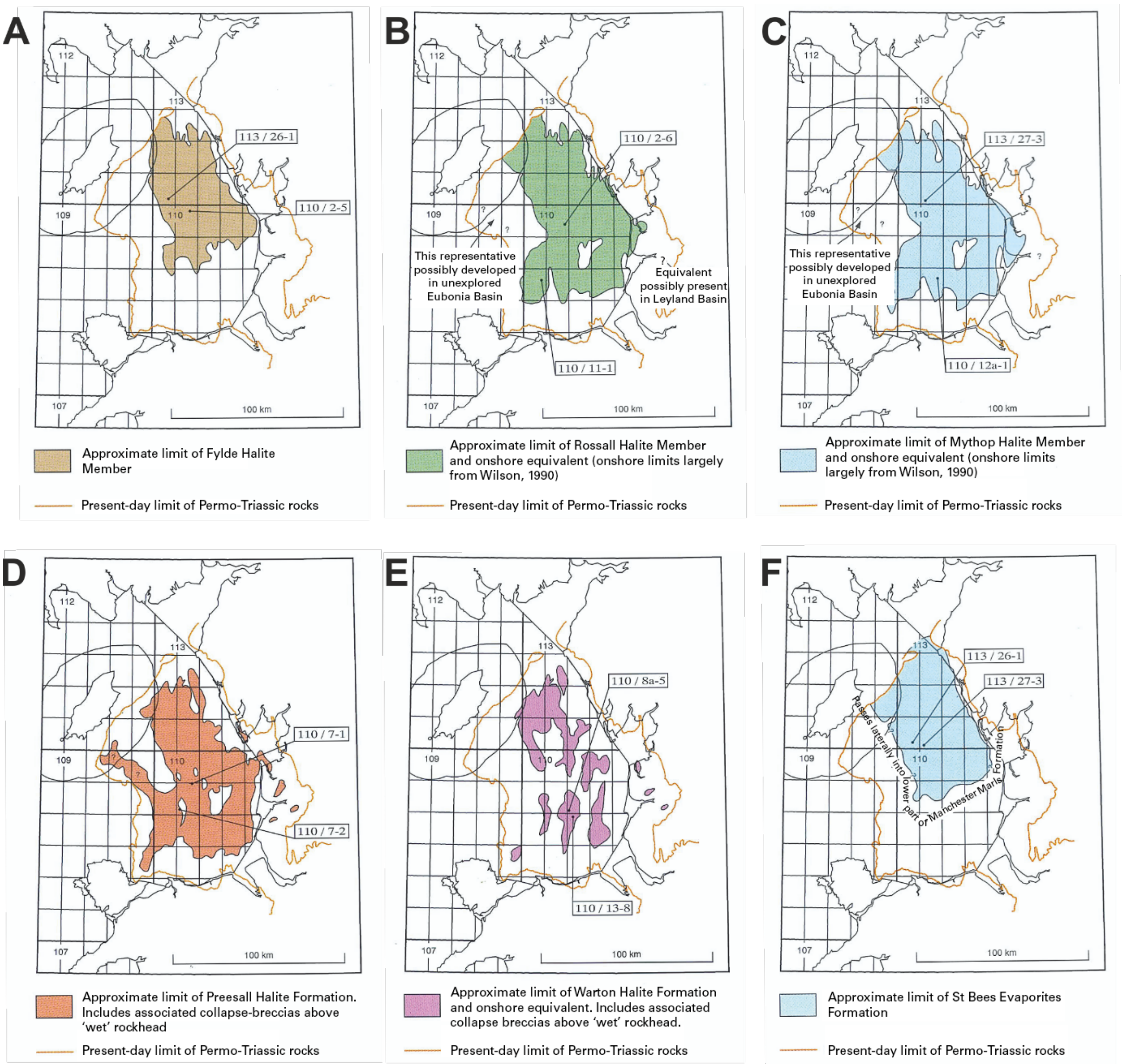

Figure 9 Distribution of the five principal halites recorded in the East Irish Sea: A) the Fylde Halite Member; B) the Rossall Halite Member; C) the Mythop Halite Member; D) the Preesall Halite Member; E) the Warton Halite Formation; F) the St Bees Evaporites Formation (from Jackson and Johnson, 1996). A to E belong to the Mercia Mudstone Group and F belongs to the Cumbrian Coast Group. British Geological Survey © UKRI 2018

In south Cumbria, the thickness of the Mercia Mudstone Group, and particularly the component Preesall Halite Member, are constrained by numerous boreholes (Rose and Dunham, 1977). The base of the group is modelled in NGS3D to a depth of 450 m below Walney Island. Offshore, the base deepens considerably to the west, proved in the hydrocarbon boreholes 113/29a-3 (89.0 to 297.18 m depth), 113/28-2 (from 125.88 to 442.87 m depth) and 113/28-1 (from 123.44 to 2379.8 m below OD). In the latter borehole, the bases of the Warton Halite Formation (96.3 m thick) at 216.4 below OD, Preesall Halite Formation (409 m thick) at 1595.9 m, the Mythop Halite Member (193.7 m thick) at 1970.4 m, and Rossall Halite Member (23.2 m thick) at 2341.5 m below OD are recorded.

Rock type description

The Penarth Group (above the depth range of interest) of north Cumbria comprises an upper 5 m succession of the Lilstock Formation comprising an uppermost pale grey, nodular, micritic limestone, 0.8 m thick, underlain by pale grey, calcareous mudstones with siltstone laminae (Ivimey-Cook et al., 1995). The underlying 8 m-thick Westbury Formation consists of dark grey, non-calcareous mudstone with thin sandstone interbeds, becoming siltier towards the base and passing down to a fine-grained sandstone with mudstone partings (Ivimey-Cook et al., 1995).

The Mercia Mudstone Group comprises mainly red or brown mudstone, locally with significant thicknesses of halite (locally 35 to 55 per cent of basinal successions offshore) and minor dolostone, dolomitic mudstone, nodular gypsum-anhydrite and common gypsum veins, and with minor and sporadic thin beds (generally less than 2 m offshore or less than 1 m in the Solway lowlands) of very fine-grained sandstone present throughout the succession in this region (Jackson and Johnson, 1996; Holliday et al., 2004; Stone et al., 2010). Halite is subject to plastic flow at depth, which may result in contortion and rapid lateral changes in thickness. This has been interpreted as causing some uncertainty in the correlation of the thick halite successions present offshore with the thinner onshore successions (Jackson et al., 1995).

In north Cumbria, it is not possible to distinguish between the Branscombe Mudstone and Sidmouth Mudstone formations and the Tarporley Siltstone Formation is not recorded from the lowermost part of the succession. The Blue Anchor Formation, recognised as 6 m thick in north Cumbria by Ivimey-Cook et al. (1995), comprises grey-green, dolomitic mudstone, but is not mapped as a distinct unit. A bed of halite, interpreted by Holliday et al. (2004) as the equivalent of the Preesall Halite Formation, was penetrated in the Silloth 1A Borehole (171–177 m depth); otherwise there is no indication that thick halites are present onshore in this part of the region.

The Warton Halite Formation, although occurring within the region, does not occur within the depth range of interest and it thus not described further. The Preesall Halite Formation (offshore) or Member (onshore) comprises clean halite with thin partings of red-brown or pale brown mudstone and grey-brown siltstone (typically less than 3 m, but up to 15 m in Borehole 113/27-1) and is considered the thickest and cleanest of the Mercia Mudstone Group halites in the East Irish Sea (Jackson and Johnson, 1996). This halite shows marked thickness variation ranging from around 600 m in basins to about 100 m on blocks (Jackson and Johnson, 1996).

The Mythop Halite Member comprises individual beds of halite ranging from l–30 m, separated by significant and laterally persistent intercalations and thicker units of red-brown, silty and micaceous mudstone (up to 35 m thick), together with minor, grey-green, calcareous siltstone, very fine-grained sandstone, anhydrite and dolomite (Jackson and Johnson, 1996). The member ranges from 51.5 to 249.9 m but likely thins towards the west Cumbria coast (Jackson and Johnson, 1996), where the thickness is not known.

The Rossall Halite Member consists of beds of halite separated by subordinate but persistent intercalations of silty, red-brown mudstone (4–6 m thick but ranging up to 12.5 m), isolated beds of grey or green-grey, micaceous, commonly dolomitic siltstone (1–3 m thick) and scattered anhydrite veins and nodules (Jackson and Johnson, 1996). The halites, which are less pure than the Preesall Halite and Warton Halite member s, comprise four beds that thicken upwards in the succession from 5−40 m thick (Jackson and Johnson, 1996). The member is up to 148 m thick, with thinning of the member to the east accompanied by progressive loss of the lower halites (Jackson and Johnson, 1996). The feather edge of the Rossall Halite Member runs beneath Walney Island (Rose and Dunham, 1977).

The Fylde Halite Member comprises beds of halite with subordinate, intercalated, laterally persistent, light grey and green-grey, silty, micaceous mudstone (3–6 m thick) and siltstone (3–5 m thick, exceptionally over 10 m), and very scarce, thin anhydrite and sandstone beds (up to 3 m thick) (Jackson and Johnson, 1996). In Borehole 113/26-1, the member is 182.5 m thick and consists of eight main beds of halite that broadly thin upwards, ranging from 5–30 m thick (Jackson and Johnson, 1996).

In south Cumbria, the succession is restricted to the Sidmouth Mudstone Formation. The component Preesall Halite Member is present onshore, where it is greater than 100 m thick (Rose and Dunham, 1977), but too shallow to be in the depth range of interest, thickening offshore westwards of the Lake District boundary fault to greater than 400 m (in Borehole 113/28-1) but below the depth range of interest.

4.2.1.2 CUMBRIAN COAST GROUP AND UNDIVIDED PERMIAN ROCKS (OFFSHORE ONLY) — LSSR AND EVAP

The Cumbrian Coast Group is present in west and south Cumbria (comprising a basal St Bees Evaporite Formation and overlying St Bees Shale Formation) and adjacent East Irish Sea (with a basal St Bees Evaporite Formation and overlying Barrowmouth Mudstone Formation) and in the Solway lowlands of the Carlisle basin and Vale of Eden (Eden Shales Formation). In the East Irish Sea (offshore of west Cumbria), where subdivision of the succession is more poorly constrained through an absence of suitable borehole data, the unit cannot be distinguished in seismic models from the underlying arenaceous-dominated strata of the Appleby Group, and is therefore classified as undivided Permian rocks.

The Eden Shales Formation, about 60–100 m thick and broadly northward-thickening (Holliday et al., 2005), occurs at crop north of the Solway Firth and dips southwards below Triassic strata of the Sherwood Sandstone Group. It typically rests conformably above the Appleby Group (Penrith Sandstone Formation) within the Vale of Eden and the Carlisle basin. In turn, the unit is overlain by sandstone-dominated strata of the Sherwood Sandstone Group.

The offshore Barrowmouth Mudstone Formation typically ranges from 83–135 m (Jackson and Johnson, 1996), but may be as little as 30 m off the west Cumbria coast (Arthurton and Hemingway, 1972). In west and south Cumbria, the St Bees Shale Formation, lateral equivalent of the offshore Barrowmouth Mudstone Formation, ranges from 0–215 m. The formation thins abruptly onshore towards the Lake District and is overlapped gradationally by the Sherwood Sandstone Group (Jackson et al., 1987).

The offshore Barrowmouth Mudstone Formation and onshore St Bees Shale Formation are both underlain by the St Bees Evaporite Formation. The thickness of the latter decreases from more than 200 m offshore (Jackson et al., 1987), particularly where the formation is dominated by halite, to around 50 m in boreholes in the Sellafield area and to less than 10 m near Gosforth (Akhurst et al., 1997), with halites being largely absent onshore. The group, present at crop in the Whitehaven area, extends westward below younger Permo-Triassic strata.

Principal information sources

The Eden Shales Formation has been proved in boreholes in the Solway lowlands (Carlisle basin), but the distribution in the Vale of Eden is based largely upon surface mapping. In the north of the Carlisle basin the formation is proved at depth in the Silloth 1A Borehole from 933.3 to 870.5 m (Holliday et al., 2004) and in Fisher Gill Borehole from 735.0 to 784.5 m. The succession shallows in the south of the basin, proved in the Bank End Maryport Borehole from 86.3 to 166.88 m, thinning appreciably to the east where it is proved in the Westnewton 1 Borehole from 199.6 to 181.4 m. In the NGS3D model the unit is interpreted to largely occur at depths shallower than 200 m below NGS datum in the south of the basin. Seismic reflection data in the Carlisle basin, and at the northern margin of the Vale of Eden, indicate that the basal part of the Eden Shales Formation is essentially conformable with, and overlaps, the underlying Penrith Sandstone Formation (Holliday et al., 2004). In the Vale of Eden, the modelled distribution of this unit in the NGS3D model is consistently shallower than 200 m below NGS datum.

The St Bees Shale Formation is known mostly from boreholes around Sellafield (Akhurst et al., 1997) including Sellafield No. 3 Borehole from 1269.24 to 1133.98 m depth. In south Cumbria, the formation is present in the Haverigg Haws Borehole from 493.75 to 265.77 m and occurs at crop in Barrow-in-Furness, being proved at shallow depths in the Roosecote Borehole from 143.75 to 99.5 m.

The distribution and thickness of the Barrowmouth Mudstone Formation in the Irish Sea is known from borehole data present west of the study area (Jackson and Johnson, 1996) and cannot be constrained as a distinct unit within the area of interest. The succession is estimated to be about 100 m thick, thinning towards to the Cumbrian coast.

The St Bees Evaporite Formation has a limited area of crop south of Whitehaven, where only the basal carbonate (limestone and dolostone) unit is well exposed. The rest of this complex succession is known mainly from boreholes (Arthurton and Hemingway, 1972). It is proved from 1315.22 to 1269.24 m depth in the Sellafield No. 3 Borehole, The formation is shown in the Haverigg area and Duddon estuary towards Walney Island, and is proved in the Haverigg Hawes Borehole from 512.95 to 493.75 m depth.

In the East Irish Sea (offshore of west Cumbria), the unit cannot be distinguished in seismic models from the underlying, arenaceous-dominated strata of the Appleby Group. In the Irish Sea area there are numerous seismic sections acquired and interpreted as part of the Nirex study (Evans et al., 1995). The reliance on these data, with no corroborating boreholes and exposure, has resulted in the Permian succession being undivided in the NGS3D model (the unit cannot be distinguished from the underlying, arenaceous-dominated strata of the Appleby Group). Within this area, the strata are modelled in the Solway Firth as a broad, faulted syncline. The dip is generally to the north-west offshore of Maryport with near coastal strata being shallower than 200 m, whereas in the axis of the syncline, in the central part of the Solway Firth, the strata are deeper than 1000 m. Offshore, from St Bees to Sellafield the unit is modelled between 200 and 1000 m, whereas offshore from Sellafield to Walney Island it is generally deeper than 1000 m.

Rock type description

The Eden Shales Formation comprises reddish-brown, micaceous siltstones, interbedded with thin beds of fine-grained sandstone and some conglomerates and breccias less than 1 m thick. In the Vale of Eden there are four distinct evaporite beds, the lowest of which is anomalous in that it includes halite along with the gypsum and anhydrite found in the other evaporite beds (Stone et al., 2010). Gypsum veins are disseminated throughout the formation.

The St Bees Shale Formation comprises mainly red siltstones, mudstones and silty mudstones, with subsidiary very fine-grained sandstone, mudstone breccias and gypsum, the latter present throughout as veins. Nodules of gypsum, anhydrite, dolomite and silica are present locally and increase in abundance towards the base of the formation (Akhurst et al., 1997).

Offshore, the St Bees Evaporite Formation is characterised by a thick sequence of evaporites (predominately halite, locally greater than 100 m thick, and anhydrite), with intercalations and partings of mudstone (up to 10 m thick) and siltstone, and a basal carbonate or calcareous siltstone (Jackson and Johnson, 1996). Comparatively, the onshore well penetrations of the formation comprise a condensed succession of interbedded dolomite and anhydrites (Arthurton and Hemingway, 1972).

The offshore Barrowmouth Mudstone Formation comprises red-brown, generally calcareous, silty mudstone and anhydrite mudstone, interbedded (up to 3 m beds) with, and passing laterally on local scales to orange–red-brown, micaceous, typically calcareous siltstone, with siltstones more abundant in the middle 30 m of the succession (Jackson and Johnson, 1996).

4.2.1.3 ZECHSTEIN GROUP — EVAP

The Permian Zechstein Group crops out in the east of the region along the coast from Sunderland to Hartlepool and inland to Darlington. Knowledge of its distribution and lithology in the subsurface is derived mostly from exploration boreholes for hydrocarbons and evaporite minerals. The Zechstein Group rocks are highly variable both laterally and vertically. Halite is subject to plastic flow at depth, which may result in contortion and rapid lateral changes in thickness.

The Zechstein Group occurs at the depth range of interest in a small area onshore around Middlesbrough and Hartlepool and extends north-eastwards offshore. In this area, the group consists of several major sedimentary cycles, with limestone and dolostone, mudstone siltstone and sandstone passing up into a varied suite of evaporite minerals including sulphates (e.g. anhydrite, gypsum, polyhalite) and halides (e.g. halite, potash) (Smith, 1974).

Principal information sources

These halite rocks are known solely from exploration boreholes for evaporite minerals and hydrocarbons, including the Seal Sands No. 1 Borehole, which proves a single halite unit from 525.2 to 482.5 m depth. This halite shallows northwards, occurring below 200 m depth, where the Zechstein Group underlies the Sherwood Sandstone Group south of Hartlepool. Given the lateral heterogeneity of the halite and its absence from the near surface, thus lacking a mapped outcrop, the depth of the halite northwards of Seal Sands No. 1 Borehole is quite uncertain.

Rock type description

The single halite is attributed to the Fordon Evaporite Formation, a thick (up to 90 m in Northern England) and varied sequence of evaporites including anhydrite and halite, with some gypsum and dolostone (Stone et al., 2010). The unit passes laterally into the ‘Seaham Residue’, a 9 m-thick limestone and dolomitic clay residue following dissolution of the evaporitic minerals, at outcrop and at shallow depths south of Sunderland.

4.2.2 Older sedimentary and igneous rocks

4.2.2.1 WARWICKSHIRE GROUP — LSSR

The Warwickshire Group is subdivided into two distinct lithological units present in different parts of the region: a siltstone and sandstone-dominated unit with subordinate mudstone, which equates to the Whitehaven Sandstone Formation, and a more heterogeneous succession of mudstone, siltstone and sandstone with coals, which equates with the Eskbank Wood, Canonbie Bridge Sandstone and Becklees Sandstone formations.

The Whitehaven Sandstone Formation (at least 280 m thick) is limited in extent to the Whitehaven area of west Cumbria (Akhurst et al., 1997; Dean et al., 2011), based upon surface mapping and present at depths shallower than 200 m. Consequently, this unit is not discussed further.

The Warwickshire Group is present in the depth range of interest in the Canonbie district north of Carlisle, within the axis of the Solway Syncline, and comprises, in descending order, the Becklees Sandstone, Canonbie Bridge Sandstone and Eskbank Wood formations (Jones et al., 2011; Dean et al., 2011), which have a combined thickness of about 500 m and are inferred to extend south-westward beneath the Solway area within the core of the Solway Syncline (Jones et al., 2011). The group is considered to be removed by the unconformity at the base of the Permian succession outside of the Solway Syncline; towards the Vale of Eden the group is absent at crop. The group rests conformably upon strata of the Pennine Coal Measures Group. There can be difficulties in distinguishing the Warwickshire Group from reddened Pennine Coal Measures Group; the distinction relies upon petrographical and palaeontological evidence, little of which is available in borehole records. Uncertainty can also result from the historical description of the Warwickshire Group succession as ‘Upper Coal Measures’, with no distinction made with the Pennine Upper Coal Measures Formation, which is locally present in the study area.

Principal information sources

The group is locally exposed in a small area around Canonbie (Jones et al., 2011). At this eastern extent of the unit the group is shallower than 200 m depth, but elsewhere is shown extending within the depth range of interest. The full thickness of the group is proved in the Becklees Borehole from 816.8 to 281.7 m and in the Fisher Gill Borehole from 861 to 798 m. Offshore, the group is not definitively proved in wells and its offshore extent is mapped only on seismic data, west of Whitehaven–Workington in the Solway basin.

Rock type description

Of the three component formations in the Canonbie area, only the lower Eskbank Wood Formation, which is 145–175 m thick, is mudstone-dominated (60 to 70 per cent (Jones et al., 2011)). It comprises interbedded red mudstone (claystones and siltstones), fine to medium-grained sandstones, calcrete palaeosols, thin beds of *Spirorbis* limestone and *Estheria*-bearing mudstones.

4.2.2.2 UNNAMED IGNEOUS INTRUSION, CARBONIFEROUS TO PERMIAN — HSR

This unit is the Whin Sill, a quartz dolerite, which extends across the north Pennines and beneath the Durham and Northumberland coalfield (Figure 4) covering an area of 4500 km^2. It comprises four distinct sills: the Farne (up to 30 m thick) and Alnwick (6–21 m) sills of north Northumberland, and the Great Whin Sill (average 30 m, but up to 90 m and thins to northern, western and southern margins, Figure 10), and the Little Whin Sill (up to 13 m thick), both of the north Pennines (Stone et al., 2010).

Principal information sources

The total thickness of the unit is presented in Figure 10. The unit is shallower than 200 m depth in the Cheviot block area north of Alnmouth and large parts of the north Pennines. However, the unit is proved within the depth range of interest around Weardale in the Rookhope Borehole (Figure 3) between 214.58 and 273.33 m and Allenheads 1 Borehole from 231.98 to 303.05 m, and south and west of Alnmouth, e.g. the Longhorsley 1 Borehole proved two leaves from 461.47 to 527.61 m and 903.12 to 929.94 m. The unit broadly deepens to the east, where it is present beneath the coalfields and is recorded in the depth range of interest around Bishop Auckland, e.g. in the Woodland 1 Borehole from 469.8 m to the base of the hole at 487.68 m, and in the Roddymoor Borehole from 525.07 to 582.09 m. In the Newcastle upon Tyne–South Shields area the unit also occurs at the depth of interest, e.g. in the Throckley Borehole from 505.27 to 543.8 m. The upper Great Whin Sill and lower and thinner Little Whin Sill were proved in the Newcastle

Geothermal Borehole at 726.0 to 813.5 m and at 1058.0 to 1096.5 m and in the Harton Dome 1 Borehole at 881.8 to 943.1 m and 1339.3 to 1372.8 m.

Rock type description

The flat-lying, sheet-like intrusive bodies comprise tholeiitic quartz dolerite, locally columnar jointed (Stone et al., 2010). The sills show sharp contacts, though locally irregular, within the Carboniferous strata that they intrude and locally rafts of this country rock can occur towards the base of the Great Whin and Alnwick sills. Vesicles are present in the marginal zones of the Great Whin Sill and large, flattened amygdales up to 1.5 m long are present in the Farne Sill. Thermal metamorphism of the adjacent country rock, for example evident 425 m above and 180 m below the sills present in the Harton Dome 1 Borehole, includes recrystallisation of limestone, increased coal rank and alteration of calcareous mudstones to a calc-silicate rock.

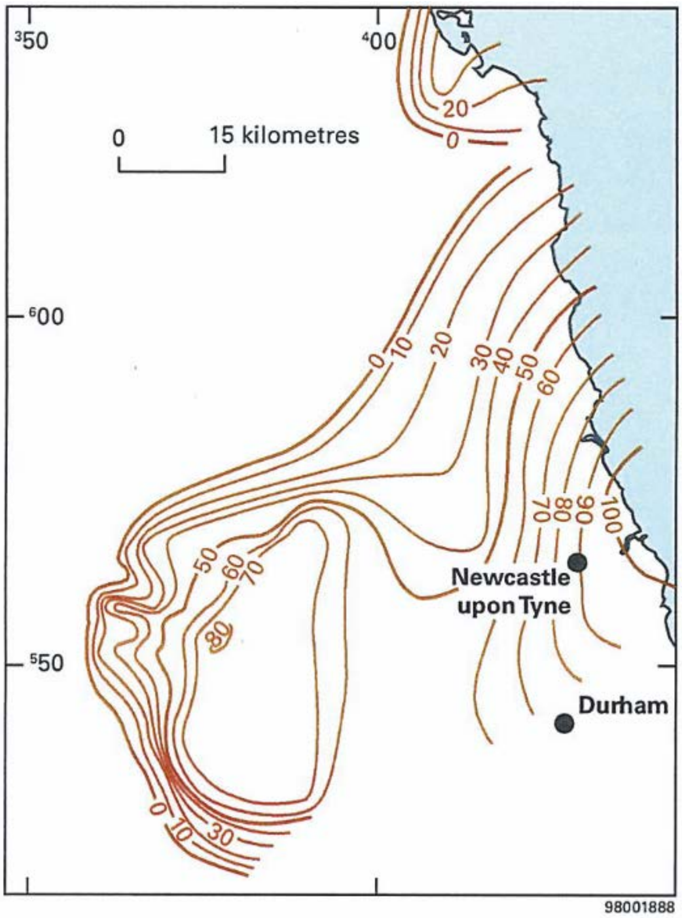

Figure 10 Isopachytes for the Whin Sill, with total thickness shown where more than one leaf is present (Stone et al., 2010). British Geological Survey © UKRI 2018

4.2.2.3 Inverclyde Group — HSR

This unit is present at crop in Scotland and in the north of the region, but extends southwards to increasing depths in the Solway Firth (where it is up to 640 m thick) and across the Cheviot Hills and northern parts of the north Pennines (where it is up to 900 m thick), with similar, southward deepening and thinning. It typically comprises a succession, in descending order, of the Ballagan and Kinnesswood formations, commonly with an intervening HSR succession including the Birrenswark Volcanic Formation in the Solway basin; the Kelso Volcanic Formation on the northern margin of the Northumberland basin, and the Cottonshope Volcanic Formation in the Cheviot Hills. Each of these formations is described in detail in Dean et al. (2011). The group rests unconformably upon Silurian strata. The Birrenswark Volcanic Formation is up to 60 m thick; the Kelso Volcanic Formation up to 150 m thick, and the Cottonshope Volcanic Formation up to 24 m thick. The group is present mostly in the subsurface and is poorly constrained.

The Ballagan Formation may show some lateral southward passage into the Lyne Formation (Border Group). The latter is considered to rest conformably upon the former (Dean et al., 2011), though in borehole records the two may be difficult to distinguish and it is possible that the Inverclyde Group is more widespread than is shown in the NGS3D model. The Ballagan Formation, which is up to 430 m thick in the Tweed basin, contains the thickest mudstones and extends within the depth range of interest between the Cheviot Hills and the North Sea coast. The mudstones of the Ballagan Formation are considered to be unsuitable for inclusion as LSSR PRTI on the basis that the mudstones are not considered to be sufficiently self-sealing.

Principal information sources

The formations have not been subdivided in the NGS3D model, in part because the group is present mostly in the subsurface and is poorly constrained. The group is present at crop in the Kirkbean area of Scotland (north of this region), and in the subsurface, ranging from 140 m below NGS datum along the Dumfries coast to 4300 m below NGS datum around Silloth in the south and in the east around Gretna, the increasing depth reflecting the position within the western limb of the Solway Syncline. The group has not been proved in wells in the offshore Irish Sea.

Rock type description

The Inverclyde Group comprises a broad range of lithologies that include: interbedded, red, fine to coarse-grained sandstones, siltstones and conglomerates (Kinnesswood Formation); interbedded grey sandstones, mudstones, limestones, dolostones and locally anhydrite (Ballagan Formation), and basalt lavas (the Birrenswark Volcanic, Kelso Volcanic and Cottonshope Volcanic formations). Only the basalt lavas are considered as possible HSR PRTIs.

4.2.3 Basement rocks

4.2.3.1 UNNAMED EXTRUSIVE ROCKS, SILURIAN TO DEVONIAN: MAFIC LAVA AND MAFIC TUFF — HSR

This unit, which equates with the Cheviot Volcanic Formation (Reston Group), is present at outcrop in the Cheviot Hills area of northern Northumberland (Figure 4), where it unconformably overlies tightly folded and cleaved Silurian strata. The areal extent at outcrop is approximately 600 km^2 and the unit is up to 500 m thick (Stone et al., 2010).

Principal information sources

The succession is mainly known from surface outcrop, and is not proved in any of the boreholes present in the NGS3D model, the subsurface extent being extrapolated from the surface outcrop based on inferred structure. To the north of the Cheviot Hills, the succession is modelled to be southward-dipping, occurring to a depth of about 600 m below NGS datum. To the south-west of the Cheviot Hills, the unit is less extensively developed, but is locally present within the depth range of interest.

Rock type description

The unit comprises stacked trachyandesite and subordinate trachyte sheets with one or more sheets of rhyolite present near the base; the succession is locally intercalated with red sandstone (Stone et al., 2010).

4.2.3.2 UNDIVIDED SILURIAN ROCKS — HSR

This unit is present both at outcrop and in the depth range of interest in the southern Lake District, equating with the Stockdale, Tranearth and Kendal groups of the Windermere Supergroup.

The Stockdale Group represents the oldest Silurian strata of the Supergroup and attains a maximum thickness of 120 m, comprising the Skelgill and Browgill formations (Stone et al., 2010; defined as Skelgill Mudstone Formation and Browgill Mudstone Formation by Millward and Stone, 2012). The overlying Tranearth Group represents up to several hundred metres of strata including the Brathay Formation (Stone et al., 2010; defined as Brathay Mudstone Formation by Millward and Stone 2012). The Tranearth Group is separated from the Kendal Group by the sandstone-dominated Coniston Group (not a PRTI). The Kendal Group is a turbidite succession up to 4.5 km thick that includes the mudstone-dominated Bannisdale Formation (Barnes et al., 2006; Stone et al., 2010). The Bannisdale Formation (defined as Bannisdale Mudstone Formation by Millward and Stone, 2012) is both underlain and overlain by turbiditic sandstones of the Coniston Group and Kirkby Moor Formation (defined as Kirby Moor Sandstone Formation by Millward and Stone, 2012) respectively. A further small outcrop area occurs south-west of the Cheviot Hills, equating with the Riccarton Group (modelled as a separate unit in NGS3D, and not a PRTI).

Principal information sources

The Windermere Supergroup succession is mainly proved from surface outcrop, not being proved in the region by any of the boreholes present in the NGS3D model; the subsurface extent is largely extrapolated from the surface outcrop based on inferred structure and is relatively uncertain. Within this area of outcrop, the base of the unit broadly deepens to the south, with overprinted tight folding (Barnes et al., 2006). Because of the generally steep southward dip of the succession, the unit typically extends within the depth range of interest beneath much of the extent of outcrop, with parts of the unit occurring depth range of interest in the south around Barrow-in-Furness–Morecambe Bay–Carnforth.

The Windermere Supergroup, including its lowermost component, the Dent Group (described as part of the undivided Ashgill rocks) PRTI, is represented in NGS3D by a highly generalised interpretation based on 1:625 000 map data. The treatment of the succession including stratigraphical representation of some parts of the Windermere Supergroup differs between 1:625 000 map data and larger-scale map data.

Rock type description

The Skelgill Mudstone Formation (Stockdale Group) is predominantly a laminated and massive mudstone and siltstone. The basal part of the formation is represented by a thin limestone that is immediately overlain by a bentonitic claystone (Millward and Stone, 2012). The Browgill Mudstone Formation (Stockdale Group) is a grey-green or red mudstone and siltstone with interbedded, subordinate beds of black mudstone. The overlying Brathay Mudstone Formation of the Tranearth Group is characterised by a succession of finely alternating laminations of muddy siltstone and carbonaceous mudstone (Millward and Stone, 2012).

The Bannisdale Formation of the Kendal Group consists predominantly of mudstones and silty mudstones. A mica-defined cleavage is present where these rocks are intensely folded within the Bannisdale Syncline and adjacent structures. The formation also includes subordinate ‘turbidite’ beds of siltstone and fine-grained sandstone that grade up into mudstone (Barnes et al., 2006), and also rare beds of limestone. Medium to thick-bedded sandstones are present in the lowermost part of the formation, representing a gradual transition into the underlying sandstone-dominated upper part of the Coniston Group (Barnes et al., 2006).

4.2.3.3 UNDIVIDED ASHGILL ROCKS — HSR

This unit is present at outcrop in the south Lake District, and occurs within the depth range of interest in a narrow zone between the Duddon valley and to the north of Windermere and in parts of the south-east Lake District. It equates with the lowermost part of the Windermere Supergroup (Dent Group). In the lower part of the succession, the Drygill Mudstone Formation reaches a thickness of at least 200 m. The Dufton Mudstone Formation (present in the Cross Fell area) has a maximum thickness of about 400 m. Mudstones in the upper part of the succession (Ashgill Formation; defined by Millward and Stone 2010 as the Ash Gill Mudstone Formation) and are typically less than 25 m thick, but thicken up to 215 m around Ulverston. Volcanic rocks include the Yarlside Volcanic Formation, comprising up to 185 to 325 m of rhyolitic ignimbrites associated with bedded tuffs and volcaniclastic sediments, and the rhyolitic tuffs of the Appletreeworth Formation (up to 5 m), Cautley Volcanic Member (up to 25 m) and Dam House Bridge Tuffs (up to 40 m) (Millward, 2004; Barnes et al., 2006; Stone et al., 2010).

Principal information sources

The succession is mainly proved from surface outcrop, not being proved in any of the boreholes present in the model. At outcrop the succession dips steeply to the south and rapidly extends through and below the depth range of interest.

Rock type description

The Dent Group comprises a varied succession of mainly calcareous mudstone with limestone nodules, subordinate calcareous sandstone, limestone, mudstone, pyroclastic rocks, rhyolite lava, sandstone and siltstone. The Drygill Mudstone Formation is characterised by fissile, thinly bedded and laminated calcareous mudstone and siltstone. The Dufton Mudstone Formation (Dufton Shale Formation (Stone et al., 2010)) consists mostly of calcareous mudstone with sporadic limestone nodules, with volcaniclastic siltstone and sandstone in the lower part. The uppermost unit of the group, the Ashgill Formation, comprises dark blue-grey shales, distinguished from underlying formations of the group by its lower calcareous content and the near absence of limestone nodules. A mica-defined cleavage is present within the mudstones. The volcanic rocks comprise rhyolitic ignimbrites and tuffs.

4.2.3.4 Unnamed igneous Ordovician to Silurian intrusion: felsic rock — HSR

The unit equates with the Threlkeld microgranite, which intrudes the lower part of the Borrowdale Volcanic and Skiddaw groups. The unit crops out in a small area east of Keswick (Figure 11), though the concealed extent of the intrusion at depth, including within the depth range of interest, is substantially greater (Millward 2006; Stone et al., 2010).

Principal information sources

These relatively small outcrops are interpreted from gravity data, and hence with relatively low confidence, to be connected to a largely concealed laccolith, 500 to 1000 m thick and approximately 12 km^2 in area that lies above the main part of the Lake District batholith (Figure 11) and is separated from it by Skiddaw Group rocks (Lee, 1989).

Rock type description

The development at surface comprises a garnet-bearing, alkali feldspar-quartz-plagioclase-phyric microgranite, though no information is available of the concealed lithologies.

4.2.3.5 Unnamed Ordovician to Silurian igneous intrusion: mafic igneous rock — HSR

This unit equates with the Ordovician Carrock Fell Centre and crops out in a small area south of Caldbeck in northern Cumbria. The unit was intruded between the Skiddaw and Eycott Volcanic groups (Millward, 2006; Stone et al., 2010). The earliest intrusion (Mosedale gabbros) occurs in the southern part of the centre as subhorizontal sill at the base of the Eycott Volcanic Group. The Mosedale gabbro is cut, with a near-vertical intrusive contact, by later microgranitic rocks (Carrock granophyre). Later, lenticular intrusions of microgranite were emplaced in the west of the centre along the Roughton Gill Fault.

A further complex of small plugs and dykes of dolerite and gabbro intrudes the Borrowdale Volcanic Group around Haweswater where it forms an outcrop of 2.6 km^2, extending at depth to over 19 km^2 (Millward, 2006). Gravity data suggests the mafic intrusions pass down into the Lake District granitic batholith at depth of about 1 km (Lee, 1986) (Figure 11).

Principal information sources

The succession is mainly known from surface outcrop. It is not proved in any of the boreholes present in the model and therefore its distribution in the depth range of interest is uncertain. However, because of the near-vertical intrusive margins, the unit is inferred to extend through the full depth range of interest below the area of outcrop, but its total thickness is unknown.

Rock type description

The Carrock Fell centre comprises layered gabbro (Mosedale gabbros), intruded by subhorizontal dolerite sills. The Mosedale gabbro is in turn cut by later microgranitic rocks (Carrock granophyre) comprising micrographic microgranite with co-magmatic dyke-like intrusion of microgabbro (Millward and Evans, 2003; Millward, 2006). The Haweswater dolerite and gabbro intrusions are hornblende-bearing and locally weakly cleaved.

4.2.3.6 Undivided Ordovician volcanic rocks and sills — HSR

This unit is present in central Cumbria. It equates with the Ordovician (Caradoc) Borrowdale Volcanic Group and Eycott Volcanic Group (Figure 4), which overlie the Skiddaw Group unconformably (Barnes et al., 2006; Stone et al., 2010). The Borrowdale Volcanic Group forms the heart of the Lake District, including Borrowdale, Scafell, Wasdale and the Duddon valley and has a cumulative thickness of at least 6000 m. The Eycott Volcanic Group is present within the northern part of the Lake District and is more than 3200 m thick.

Principal information sources

The succession is mainly proved from surface outcrop, but the Borrowdale Volcanic Group is also proved in the Sellafield 3 Borehole from 1623 m to the base of the hole at 1952 m. The unit is present within the depth range of interest throughout most of the area of outcrop in central Cumbria between Scafell and Patterdale in the north and Coniston and Ambleside in the south, but is deeper than 1000 m where present beneath the Windermere Supergroup in south Cumbria and below Triassic strata in west Cumbria (as for the Sellafield 3

Borehole). Despite the limited presence of suitable boreholes, the presence of excellent exposure within an area of marked topographical range in excess of 900 m provides very good constraint on the subsurface distribution of this unit within the depth range of interest. The aeromagnetic anomaly associated with the Eycott Volcanic Group shows that the main outcrops in the northern part of the Lake District and in the northern part of the Cross Fell inlier are linked beneath Carboniferous strata and truncated to the south by the Causey Pike Fault (Stone et al., 2010).

Rock type description

The Borrowdale Volcanic Group comprises basalt, andesite and dacite, and pyroclastic rocks, along with associated dykes and sills and many intercalations of volcaniclastic sedimentary rocks; hydrothermal alteration is locally pervasive with chemical alteration and growth of epidote, chlorite and sericite (Barnes et al., 2006). The Borrowdale Volcanic Group can be divided informally into 'lower' and 'upper' parts. The lower part represents an initial phreatomagmatic phase associated with local units of basaltic andesite tuffs varying from a few metres to greater than 600 m with abundant clasts from the underlying Skiddaw Group. This is overlain by a thick and extensive eruptive phase, mainly of andesite lavas erupted from low-profile volcanoes, forming between 30 and 90 per cent of the succession along with sills and block- and ash-flow breccias, with individual lava sheets between 10 to 200 m thick and mapped laterally for up to 3 km (Stone et al., 2010). The upper part of the group formed during a later, dominantly silicic phase that featured voluminous eruptions of pyroclastic density currents accumulating in local, fault-controlled depocentres and resulted in caldera formation (Stone et al., 2010). Fluvial and lacustrine volcaniclastic rocks are found infilling calderas, e.g. Scafell. The Eycott Volcanic Group comprises a lower, 2400 m-thick succession of tabular basaltic andesite and andesite sheets with subordinate basalt and dacite lava sheets and sills with subordinate pyroclastic rocks. This is overlain by about 800 m of heterogeneous andesitic tuff and lapilli tuff.

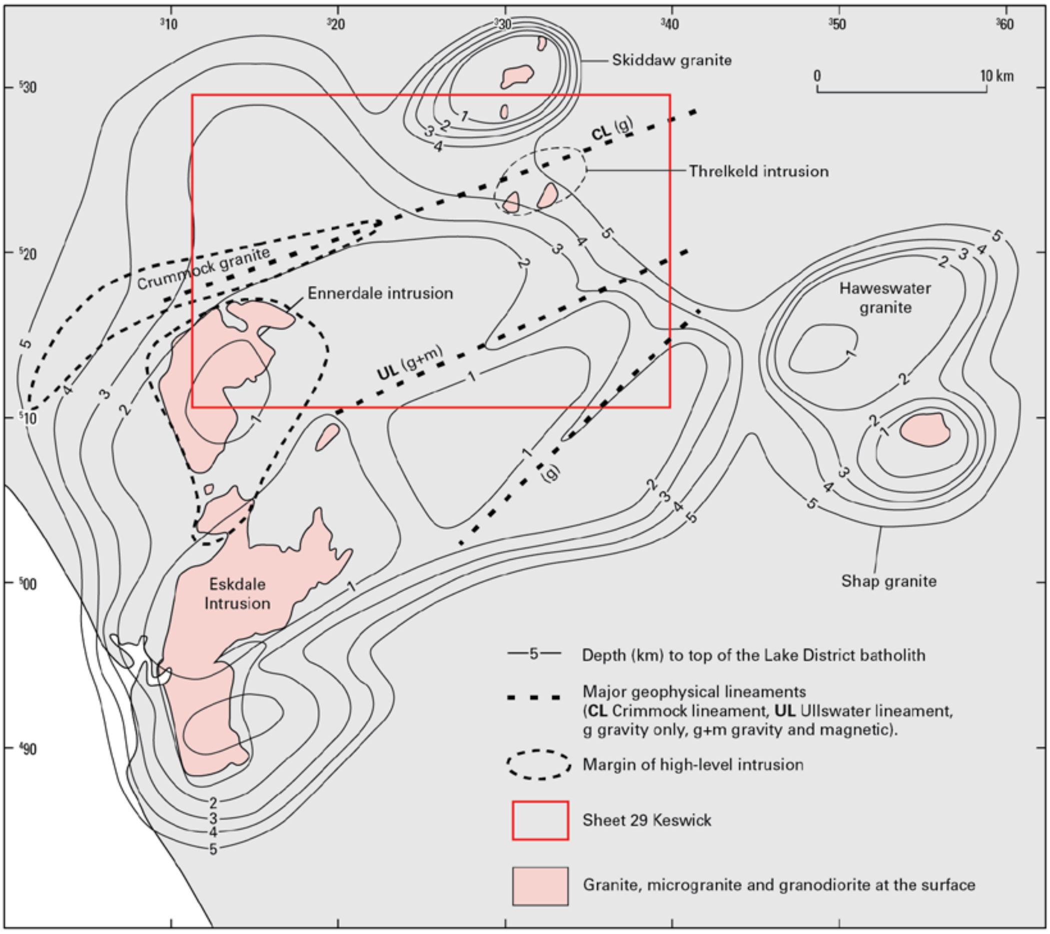

Figure 11 Surface and subsurface geometry of the Lake District batholith based on an interpretation of gravity and aeromagnetic data by Lee (1989, fig. 8.1), from Woodhall (2000). British Geological Survey © UKRI 2018

4.2.3.7 UNDIVIDED ORDOVICIAN ROCKS — HSR

This unit is present in west and north Cumbria where it equates with the Skiddaw Group of mudstones with strong slaty cleavage (Cooper et al., 2004; Barnes et al., 2006; Stone et al., 2010). The group crops out and extends to the depth range of interest over a large area in the northern part of the Lake District around Skiddaw and west of Derwent Water, and also forms the upland area of Black Combe in the south of the region. In the Furness area, south-west Cumbria, Dent Group rocks (Windermere Supergroup) overstep the Borrowdale Volcanic Group to rest directly on the Skiddaw Group. The unit extends into the depth range of interest beneath Alston, Weardale and Bishop Auckland. The unit is also present beneath the Durham and Northumberland coalfield, though below 1000 m depth. The base of the Skiddaw Group is nowhere proved and is inferred to lie at depths greater than the base of the NGS3D model.

Principal information sources

The NGS3D model shows the Skiddaw Group occurring within the depth range of interest in the Furness and Ullswater areas and underlying substantial areas of Borrowdale Volcanic Group rocks at less than 2 km below the surface in central Cumbria. In west Cumbria, the group occurs at the depth range of interest, present immediately below the Carboniferous Limestone Supergroup, proved by haematite exploration boreholes west of Egremont (Stone et al., 2010). The group is also modelled within the depth range of interest in the Alston block area of the north Pennines, with the top proved in the Allenheads 1 Borehole at 470 m and the Roddymoor Borehole at 862 m.

Rock type description

The Skiddaw Group comprises mudstone, siltstone and sandstone, and the varying proportions of these components have been used to erect a formal lithostratigraphical subdivision within the group (Cooper et al., 2004). These rocks are also structurally complex as a result of the combination of syndepositional slumping and later tectonic deformation (Cooper et al., 2004).

4.2.3.8 INTRUSIVE IGNEOUS ROCKS — HSR

This unit comprises the surface and subsurface presence (Figure 4) of the Lake District batholith and Cheviot pluton, and the subsurface presence of north Pennines batholith (Stone et al., 2010). The Lake District batholith (Figure 11) includes three large intrusive bodies of granitic rock of Ordovician age, which crop out in the west of the Lake District; these are the Ennerdale microgranite pluton, a 1–2 km-thick tabular body that crops out over 53 km^2 around Ennerdale and Wasdale; the Eskdale granite pluton, which also has an outcrop of 53 km^2 centred in Eskdale and on Muncaster Fell, and the Broad Oak granodiorite pluton of 23 km^2 extent from Waberthwaite to Bootle. The upper levels of the Lake District batholith are of Early Devonian age and include the Skiddaw granite pluton, exposed in the Caldew valley north of Keswick, and the Shap granite, quarried in east Cumbria (Figure 11). The Skiddaw granite is about 4.5 km in diameter and the Shap granite extends over 8 km^2 outcrop (Stone et al., 2010).

The north Pennines batholith (Figure 12) is a 60 km x 25 km intrusion at depth; it is elongated with a north to north-east trend.

The Cheviot pluton has an outcrop of about 60 km^2 and, at 4 km depth, a diameter of nearly 20 km (Stone et al., 2010).

Principal information sources

Outside the outcrops of the plutons of the Lake District batholith, the depth to the granites has not been proved in boreholes. Gravity studies (Bott, 1974; Lee, 1986; Lee, 1989) have shown that these intrusions are linked in the subsurface to a huge mass of granitic rocks that underlie much of the central part of the Lake District (Figure 11). The shape of the top surface of the batholith has been investigated through interpretation of the gravity and magnetic data for the region (Lee, 1989). However, the granite outcrops are not used by Lee (1989) to constrain the gravity and density models used for calculating the original 2.5 dimensional sections and they did not accurately predict the outcrops of the Eskdale and Ennerdale plutons.

Interpretation of seismic reflection data in the Gosforth to Wasdale area has revealed that the batholith comprises a stack of tabular-shaped plutons, each 1–2 km thick, and interleaved with slivers of country rock, probably Skiddaw Group (Evans et al., 1993; 1994), though the extent of the individual plutons is poorly known. It forms a cedar-tree laccolith-like form, but for the NGS3D model the batholith is taken as a single unit and the western margin is inferred to be broadly coincident with the Lake District boundary fault zone.

The batholith is interpreted through gravity modelling to lie at depths of less than about 1000 m below NGS datum over a large, ridge-like area that extends eastwards from the outcrops of the Ennerdale and Eskdale plutons (Figure 11), although, as it is largely based upon gravity modelling, the depth is likely highly uncertain. Along the southern flank of the batholith, the top surface is modelled to dip steeply to below the base of the model. The northern part of the Eskdale pluton at outcrop is almost horizontal, with marginal volcanic rocks hornfelsed. A gentle, northward dip of the batholith top is also seen at outcrop in the Keswick area and much of the southern part of the Skiddaw Group inlier is underlain by granite at relatively shallow depths. By contrast, a steep, northern contact is seen at outcrop just north of the outcrop of the Ennerdale pluton, which intrudes the Skiddaw and Borrowdale Volcanic groups, and also in the north-east of the inlier where the batholith once again rises to the surface as the Skiddaw pluton (Figure 11). The thermal aureole associated with the Shap granite, mainly a biotite hornfels within the Borrowdale Volcanic Group and Windermere Supergroup, along with gravity and magnetic geophysical data, suggest this pluton is more extensive than the area present at crop (Stone et al., 2010) and may extend to a further pluton, the Haweswater granite, interpreted only from geophysical data (Figure 11).

The north Pennines batholith is present only in the subsurface, with only the central Weardale granite pluton proved within the depth range of interest in the Rookhope and Eastgate boreholes (Figure 12), with the top of the intrusion at 390 and 270 m depth respectively (Stone et al., 2010). The extent of the granite was modelled, with some degree of uncertainty, from gravity surveys that indicate the presence of a series of broadly cylindrical plutons (Kimbell et al., 2010). Contour information on the top north Pennines batholith is shown in Figure 12, showing that the concealed tops of the Tynehead and Scordale plutons locally extend above sea level, whereas the top of the Rowlands Gill and Cornsay plutons are interpreted to lie between 0 and 1000 m below NGS datum.

The Cheviot pluton intrudes the Cheviot Volcanic Formation (Figure 4), the latter being thermally altered to up to 2 km from the intrusion (Stone et al., 2010).

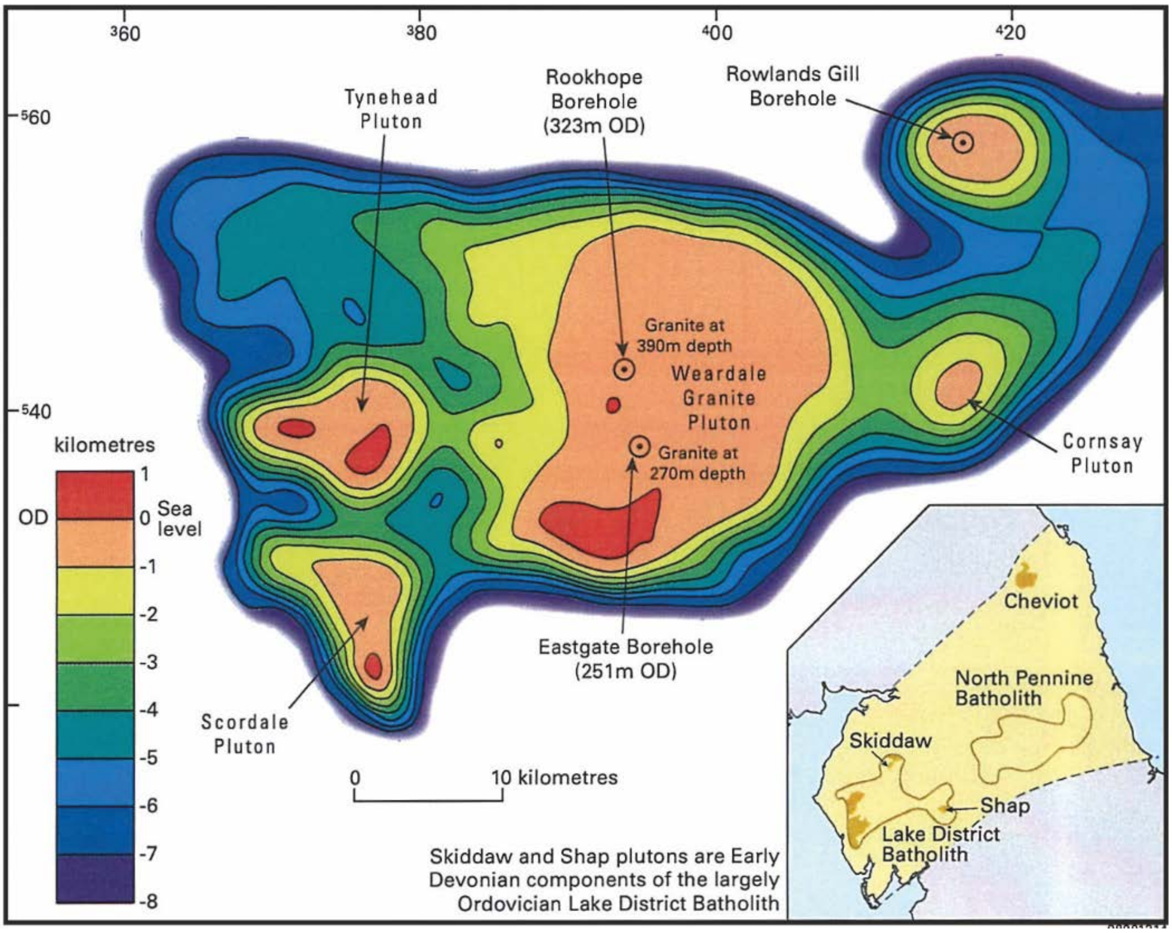

Figure 12 Contour information on the top of the north Pennines batholith (from Stone et al., 2010, fig. 36). British Geological Survey © UKRI 2018

Rock type description

The lithological composition of this unit is based upon surface outcrop, or, in the case of the Weardale granite, from boreholes. The variability of the lithologies at the depth range of interest is unknown. The Ennerdale pluton mainly comprises porphyritic granophyric granite, with dolerite and dioritic, granodioritic and granitic rocks occurring at the intrusion margins (Stone et al., 2010). The Eskdale granite consists of medium-grained, muscovite granite, aphyric and megacrystic microgranite and coarse to very coarse granite, with all but the latter locally metasomatically altered to greisens. The Broad Oak granodiorite pluton is a medium-grained hornblende granodiorite with marginal microgranodiorite, which in the south displays strong argillic alteration. The Skiddaw pluton comprises a medium-grained, biotite granite, locally porphyritic. The intrusion is surrounded by a thermal aureole within the adjacent Skiddaw Group country rock and there is pervasive alteration of the granite in the north of the outcrop to a quartz-muscovite greisen. The Shap granite is a pink and grey biotite monzogranite with up to 60 per cent feldspar crystals up to 5 cm in diameter, with microdioritic enclaves and with locally abundant xenoliths of country rock. The north Pennines batholith granite, proved in the Rookhope and Eastgate boreholes, contains biotite and muscovite with a shallow-dipping foliation and is cut by pegmatitic and aplitic dykes and tourmaline-bearing veins (Dunham et al., 1965; Stone et al., 2010). In the Rookhope Borehole, only the uppermost 2 m of granite shows weathering, with alteration of feldspars to muscovite (Dunham et al., 1965). The Cheviot pluton comprises an outer zone of grey monzonite/monzodiorite and an inner zone of medium to coarse monzogranite, with a final phase of pink, medium-grained, granophyric granite (Stone et al., 2010).

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in Northern England and shows their surface extent on a map (Figures 14 and 15). Many of the structures are well known and are identified in the BGS regional guides and memoirs. As described in the guidance (RWM, 2016a), they are relevant to safety in two ways: they may provide effective limits to any rock volume being considered for siting a GDF, and they have an impact on the uniformity and predictability of rocks and groundwater at a scale of relevance to a GDF.

The DTI (RWM, 2016b) sets outs the methodology required to identify key rock structures as defined in the guidance (RWM, 2016a): major faults and areas of folding. The rock structure DTI sets out how data and information are extracted from existing BGS 3D geological information. This includes the BGS UK3D NGM (Waters et al., 2015), which is an updated version of UK3D that includes fault objects (referred to in this section) and published reports. These are used to illustrate the structure's extent in the depth range of interest and to output them as ArcGIS shape files to produce maps. The guidance sets the depth range of interest for emplacement of a GDF between 200 and 1000 m below NGS datum and defines this as the depth range in which rock structures should be assessed. In the following discussion some reference is made to rocks and structures below the depth range of interest in order to clarify the structural setting of the region. The map highlights only those faults that were considered in the depth range of interest.

Major faults are defined as those that give rise to the juxtaposition of different rock types and/or changes in rock properties within fault zones that may impact on the behaviour of groundwater at GDF depths (see DTI, RWM, 2016b). It was judged that faults with a vertical throw of at least 200 m would be appropriate to the national-scale screening outputs since these would be most likely to have significant fracture networks and/or fault rocks and would have sufficient displacement to juxtapose rock of contrasting physical properties at the GDF scale. However, faults that do not meet the 200 m criterion but were still considered significant by the regional expert at the national screening scale of 1:625 000 were mapped and are discussed. It is recognised that many locally important minor faults would not meet this criterion and would be more appropriately mapped during regional or local geological characterisation stages.

Areas of folded rocks are considered to be important in a heterogeneous body of rock, such as interlayered sandstone and mudstone, where the rock mass has complex properties and fold limbs dip at steep angles, potentially resulting in complex pathways for deep groundwater. Where folding occurs in relatively homogeneous rock there is little change in the bulk physical properties and therefore there is less impact on fluid pathways. Hence, areas of folded rocks are defined as those where folding is extensive and/or where folding results in steep to near-vertical dips in a heterogeneous rock mass of strongly contrasting physical properties at a national screening scale of 1:625 000 (see DTI, RWM, 2016b). Their locations are indicated on the map in general terms and the nature of the folding is discussed.

Faulting in the UK is pervasive and therefore it is not practical to identify all faults and fault zones. Although any faulting can result in an area being difficult to characterise and could influence groundwater movement, it is assumed that minor faulting will be characterised in detail at the GDF siting stage and therefore only major faults, as defined above, are identified.

The majority of faults shown on BGS geological maps have been interpreted from surface information, while knowledge of faulting at depth is typically limited to areas of resource exploration where significant subsurface investigation has taken place. Faults shown on BGS geological maps are largely based on interpretation of topographical features that define stratigraphical offset and are not mapped purely on the basis of observation of fault rock distribution. Hence, in areas where the bedrock is concealed by superficial deposits, the stratigraphical units are thick and homogeneous, or there is limited subsurface data, faulting is likely to be under-represented (Aldiss, 2013). The presence of any faulting will be determined at the GDF siting stage.

5.2 REGIONAL TECTONIC SETTING

The surface and subsurface structure within the counties of Cumbria, Durham, Tyne and Wear and Northumberland, with some overlap at the southern margin into Cleveland, Yorkshire and Lancashire, are described.

Northern England is underlain by a wide variety of rocks with a geological history spanning almost 500 million years (Stone et al., 2010). The structure and concealed geology of the region can be described in terms of three major tectonostratigraphical units that are bound by unconformities and the structural complexity of which increases with depth and age. These units relate to the Acadian, Variscan and Alpine orogenies (see Pharaoh and Haslam, 2018) and for the current region, the main faults are best described in the following terms.

- Younger cover (equivalent to younger sedimentary rocks in Table 3) — structures of the strata that lie above the base Permian unconformity; deformation is localised, generally with small-scale disruptions related to Mesozoic extension and to the far-field effects of the Alpine Orogeny.
- Older cover (equivalent to older sedimentary and igneous intrusive rocks in Table 3) — structures affecting Devonian and Carboniferous sedimentary rocks.
- Early Palaeozoic basement (equivalent to basement rocks in Table 3) — comprising faulted, folded and cleaved rocks, sedimentary and igneous, both at outcrop in the west and concealed in the subsurface. Reactivation of structures developed within these rocks is thought to have played a significant role in the post-Acadian evolution of the region.

The basement rocks of the region comprise Ordovician and Silurian sedimentary, volcanic and intrusive rocks that are exposed in the Lake District and adjacent Cross Fell and Teesdale inliers in the north Pennines. Elsewhere in the region, these rocks are largely concealed and have been proved in only a few boreholes that penetrate through the late Palaeozoic cover. The basement rocks of the Lake District and Alston blocks host major granitic intrusions, referred to as the Lake District and north Pennine batholiths respectively. The central part of the former is constructed of tabular granite bodies of Ordovician age (Bott, 1974; Evans et al., 1993; 1994; Chadwick and Evans, 2005; Hughes et al., 1996; Lee, 1986), with marginal, more conical plutons of Early Devonian age (Selby et al., 2008). The north Pennine batholith beneath the north Pennines (Alston block) is a coalesced set of five plutons (Kimbell et al., 2010), the central one of which is the Weardale pluton. The shape of the north Pennine batholith beneath the Carboniferous cover of the Alston block is interpreted from gravity data and its component Weardale pluton has an Early Devonian age (Dunham et al., 1965; Bott, 1967; Kimbell et al., 2010). The Cheviot massif, formed of Early Devonian volcanic rocks, is underpinned by the conical Cheviot granite, which was emplaced during Early Devonian volcanism (Thirlwall, 1988). The basement rocks have a complex tectonic history associated with the closure of the Iapetus Ocean and subsequent Acadian cleavage and metamorphism events in Early Devonian times (Woodcock and Soper, 2006).

The Late Devonian and Carboniferous older cover rocks of the region rest with marked angular unconformity on the early Palaeozoic basement. In Late Devonian to early Carboniferous (Mississippian) times (Leeder, 1971; 1974; Leeder et al., 1989; Fraser and Gawthorpe, 2003), oblique dextral collision between Laurussia and Gondwana resulted in the north-eastwards 'extrusion' of the old continental fragment of Baltica and the fragmentation of part of the Laurussian margin to form, through dextral transtension, a mosaic of sedimentary basins across Northern England (Coward, 1993). Early Carboniferous sedimentation in Northern England was controlled by reactivated east-north-east-trending faults that lie within the hanging wall of the Iapetus suture and by an apparent 'buoyancy' effect over the rigid granitic batholiths within the basement rocks, thus dividing the region into blocks and basins (e.g. Kimbell et al., 1989, Collier, 1991; Chadwick et al., 1995; Chadwick and Evans, 2005). Over the more elevated blocks, the succession is thin and less deformed compared with that in the basins. The importance of the block and basin structure in the Carboniferous of the UK has been recognised for many years (e.g. Kendall, 1911; Marr, 1921; Versey, 1927; Trotter and Hollingworth, 1928).

From mid-Mississippian times, extensional faulting was much diminished and was gradually replaced by thermal subsidence resulting in more evenly distributed sedimentation across the blocks and basins. In late Carboniferous times, the 're-insertion' of Baltica — as a result of the closure of the Ural Ocean and the encroaching Variscan nappes in the south of the UK — caused reverse reactivation of the earlier extensional faults (Coward, 1993; Domeier and Torsvik, 2014). In Northern England these events have been interpreted as basin inversion through northerly directed compression (Chadwick et al., 1995). However, this model does not satisfactorily explain the long-standing conundrum of contrasting deformation styles that all occur within a short period of time in adjacent areas. An elegant solution has since been proposed by de Paola et al. (2005), which invokes strain partitioning, resulting in adjacent zones with contemporaneous 'pure' extension and wrench-dominated structures. The partition-bounding structures were the major faults and the angle of these to the regional transport direction critically determined the deformation style.

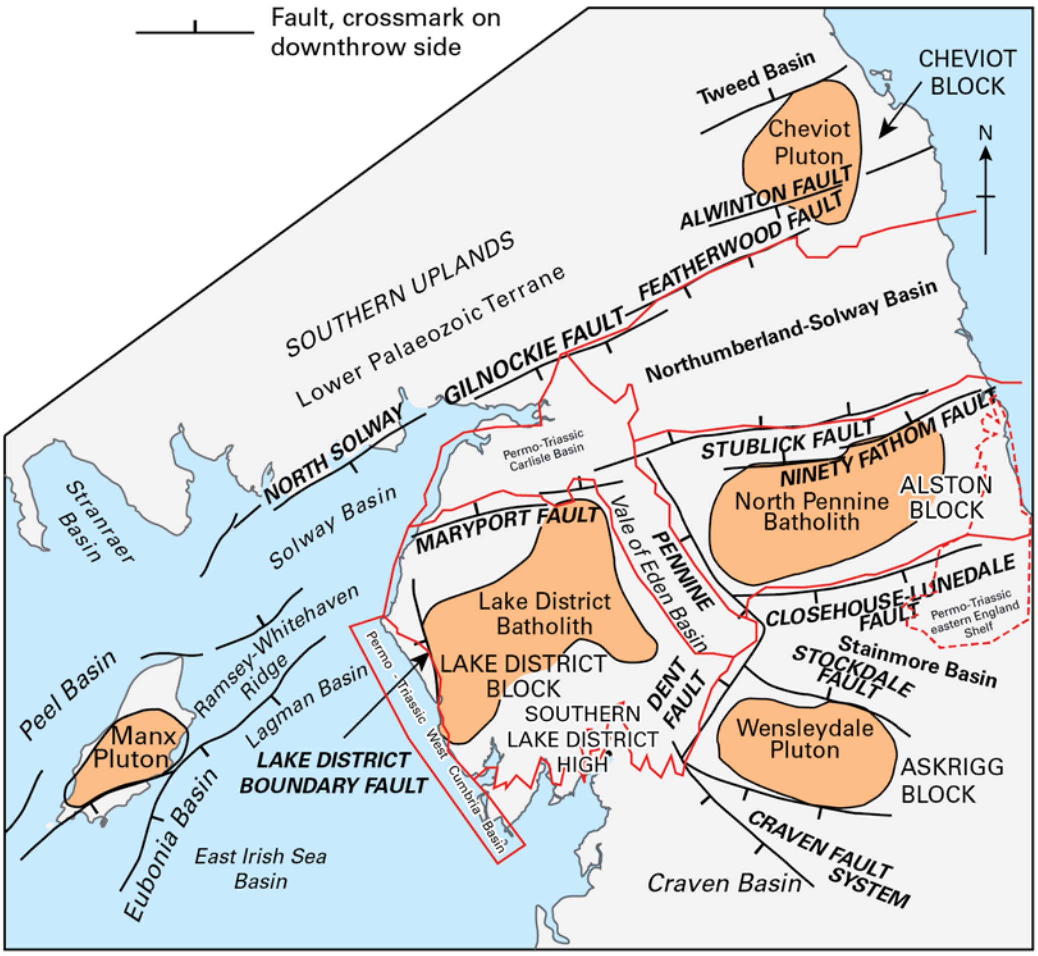

Figure 13 Main structural units recognised as controlling the distribution of younger and older cover rocks in the Northern England region (after Stone et al., 2010, fig. 7). Red lines delineate regions described in the text. British Geological Survey © UKRI 2018

By earliest Permian times, Variscan continental collision had led to the final consolidation of the Pangaean supercontinent. Associated regional uplift and erosion that developed a widespread unconformity across the region. Permian subsidence in the UK and adjacent continental shelf is thought to be a consequence of continental rifting (Holloway, 1985; Glennie, 1986). The Permo-Triassic strata were subsequently tilted and locally faulted, but are generally unfolded. Contrasting structural styles characterise their two main occurrences in the region. Permo-Triassic strata were deposited to the southeast, over the north-western reaches of the eastern England shelf, where regional subsidence occurred on the periphery of the southern North Sea basin. To the west and north-west, the Vale of Eden, Carlisle and west Cumbria areas form the onshore part of a rift system that extended southwards to the English Channel via the East Irish Sea and Scottish waters. Development of these rift basins involved partial reactivation of the Carboniferous fault network but mostly developed through the formation of a new, dominantly north–south fault system, superimposed on the older fault network.

Though the Permo-Triassic rocks of the Vale of Eden are believed to have been deposited in a half-graben (Burgess and Holliday, 1979; Arthurton and Wadge, 1981), there is as yet no conclusive evidence of synsedimentary faulting in the onshore part of the Carlisle basin during deposition of the Penrith Sandstone Formation. Similarly, there is little evidence for the nature of the structural control on Triassic to Early Jurassic sedimentation in the region.

The evolution of the region from the Mid Jurassic onwards to the Quaternary is largely conjectural as no bedrock strata deposited in that period are preserved. It is likely that the Southern Uplands and Lake District blocks remained as structurally high areas, initially subaerially exposed, but from Mid Triassic times onwards they received variable amounts of sediment. No unequivocal evidence of syndepositional faulting can be observed, and the general impression is of a gradual expansion of the depositional area consistent with a period of post-extensional regional subsidence. However, this contrasts with the offshore extension of the Carlisle depocentre, where Mesozoic synsedimentary displacement on the Maryport Fault has been presented by Chadwick et al. (1993) and in the East Irish Sea basin by Jackson et al. (1987). Extensional basin subsidence probably continued through the Jurassic and into Early Cretaceous times, being largely controlled by the Permo-Triassic structural template. A period of post-rift, regional subsidence probably followed in the Late Cretaceous. Evidence of faulting later than the Early Jurassic is widespread in the Carlisle area (Chadwick et al., 1993). However, dating of these displacements is problematic because of the limited age range of the cover rocks and their present restricted areal extent.

Cenozoic uplift probably comprised two distinct components: regional flexural uplift, possibly associated with development of the Scottish Palaeogene igneous province, and, superimposed on this, more localised uplifts corresponding to basin inversions associated with Alpine crustal compression (Chadwick et al., 1994). This episode in the history of the region is poorly understood but it is likely that features such as those of the Lake District block owe their origin more to Palaeozoic and Mesozoic patterns of differential subsidence than to later events.

Based upon the geology of the region, eight principal structural areas are recognised, the boundaries of which are generally represented by major fault zones (Figure 13). These are summarised as follows:

- Lake District, Alston and Cheviot blocks — granite-cored, early Palaeozoic basement rocks over which thin successions of older cover rocks were deposited, or from which they have been eroded. Across these the early Palaeozoic basement is at outcrop or within 1 km of the surface.
- Tweed and Northumberland — Solway basins separating the Southern Uplands and Cheviot blocks from the Lake District and Alston blocks, and the southern Stainmore basin in which thick sequences of older cover rocks were deposited. Early Palaeozoic basement beneath these generally lies at depths of about 4–5 km.
- Carlisle, Vale of Eden and west Cumbria basins and the eastern England shelf — areas of Permian and Mesozoic rocks to the east of the Pennines, over much of County Durham and extending southwards into the Eastern England region, and in the west, the Carlisle, Vale of Eden and west Cumbria basins.

Where folding is directly related to faulting, e.g. an anticline associated with a reactivated ‘blind’ fault or as fault drag along the fault, these are described in conjunction with the controlling fault. More general folding is described in a separate section.

5.3 MAJOR FAULTS

Faulting in Northern England is complex and reactivation, both in extension and compression during succeeding geological events, is a common theme of the fault history. For example, some structures cutting the early Palaeozoic rocks show evidence of synsedimentary and synvolcanic displacements and were subsequently reactivated during Acadian deformation (Millward, 2002; Woodcock and Soper, 2006). Renewed extension occurred in the early Carboniferous, exerting a fundamental control on sedimentation on the blocks and in the basins (Leeder, 1974; Gawthorpe et al., 1989). Inversion structures formed during late Carboniferous Variscan deformation and renewed extension occurred during the Permian (Chadwick et al., 1995). At least some of the major structures likely originated through reactivation of fractures in the deeper Proterozoic basement of the region. This section describes the framework of faults in the Northern England region (Figures 14 and 15). These include the Maryport–Stublick–Ninety Fathom, Closehouse–Lunedale–Butterknowle, Lake District boundary, Pennine and Dent fault zones. Several named faults described, including several that form part of larger named fault systems, are not shown as major faults in Figures 14 and 15.

The east-north-east-trending Maryport–Stublick–Ninety Fathom fault zone forms a complex, *en échelon* set of structures extending more than 200 km across the Northern England region, from offshore in the East Irish Sea in the west to offshore Northumberland in the east (Chadwick and Evans 2005). The fault zone forms the boundary between the Northumberland–Solway basin to the north and, to the south, the Ramsey–Whitehaven ridge (offshore) and the Lake District and Alston blocks (onshore).

The Maryport Fault is the western component of the fault zone. It has a length of about 21 km, a down-to-north component of vertical displacement of up to 1240 m in UK3D and a large oblique–normal displacement. Seismic reflection data suggest that the component faults in this structure dip at moderate angles (45–60˚) to the north. In places, they appear to comprise single fault planes, but more commonly the displacement is shared between several parallel faults linked together by relay or transfer ramps (Kimbell et al., 1989; Collier, 1991; Chadwick et al., 1995). The Gilcrux Fault is a splay to the south off the Maryport Fault that has a normal throw of about 500 m down to the north. The Bullgill Fault links the Maryport and Gilcrux faults and, although unproven, is interpreted to have significant downthrow to the south-west.

Evidence for repeated reactivation of the Maryport Fault includes early Carboniferous extension, followed by Variscan partial reversal during Solway basin inversion (Chadwick et al., 1993). In Permian and Mesozoic times, renewed oblique–normal displacement strongly influenced basin subsidence and a further partial reversal occurred as the Solway basin was inverted, probably in mid-Cenozoic times as a far-field response to Alpine compression.

Further south and parallel to the Maryport Fault is the Dovenby Station Fault, which has a mapped length of approximately 10 km and downthrows to the north.

From just east of Aspatria to the western margin of the Vale of Eden, the near-surface expression of the Maryport Fault is represented by a set of sinuous faults with northerly downthrow, including the All Hallows Pit, Bagrow, Crummock, Waverbank, Waver–Warnell Fell–Sebergham and Lowling–High Braithwaite faults. Though these structures have throws of only a few tens of metres at the surface, the throws increase at depth, for example to 215 m on the Crummock Fault and 360 m on the Waver–Warnell Fell–Sebergham faults (Chadwick et al., 1995). In the Vale of Eden, the Maryport–Stublick–Ninety Fathom fault zone throws the older cover and Palaeozoic basement rocks down to the north, but appears to have little effect in the younger cover rocks.

To the east of the Pennine fault zone, the Maryport–Stublick–Ninety Fathom fault zone comprises four main *en échelon* segments. The Tindale Tarn Fault has a length of about 21 km and throws down to the north. It is not currently modelled in UK3D. The Stublick Fault is the central, main segment with a length of about 36 km and a -mailto-north, normal displacement of up to 3.3 km at depth. Within the 200–1000 m depth range, it has a displacement of more than 200 m. The Ouse Burn Fault splays off south from the central section of the Stublick Fault and continues east-north-eastwards for about 35 km. It has a down-to-north displacement of about 850 m at depth and, within the 200–1000 m depth range, it maintains a throw of more than 200 m.

The Ninety Fathom Fault is the eastern segment of the Maryport–Stublick–Ninety Fathom fault zone, overlapping with, and stepped back southwards from, the Ouse Burn Fault by up to 6.5 km. Onshore its trace is almost 50 km; the displacement at depth is about 2.2 km, but within the 200–1000 m depth range it maintains a normal displacement of at least 200 m. The fault is exposed at Cullercoats Bay, 15 km east-north-east of Newcastle upon Tyne, where tight folds in the hanging-wall block attest to an element of fault reversal. A long history of movement of warm brines along this structure is implied by the occurrence of barite cementation of the Permian Yellow Sands Formation within the fault zone at Cullercoats and evidence for barium-rich brine flows in several coal mines adjacent to the fault (Younger et al., 2016).

The Closehouse–Lunedale–Butterknowle fault zone is a broadly west–east set of south-dipping *en échelon*, normal faults some 70 km long (Chadwick and Evans 2005). At its western extent it is linked to the Pennine fault zone and to the east extends into the North Sea at Hartlepool. The fault zone is parallel to the Stublick and Ninety Fathom faults and forms the southern margin of the Alston block and hence the northern margin of the Stainmore basin. In the west, the main segments include the Swindale Beck, Closehouse, Lunedale and Staindrop faults (Burgess and Holliday, 1979), which form a structure striking eastwards in the west and swinging towards the east-south-east along the Staindrop Fault segment. The length of this set of faults is more than 56 km and the displacement greater than 540 m in UK3D, however, Mills and Hull (1976) show an eastward-decreasing, near-surface throw from about 700 to 100 m along the Staindrop Fault. The Butterknowle Fault splays off the Lundale Fault to the east-north-east, extending eastwards almost 65 km. It has a variable downthrow along its length of 290 m to more than 500 m. At its eastern extent it is *en échelon* to the north of the Butterwick–West Hartlepool Fault, with which it merges some 9.5 km offshore. This fault has a length of about 37 km and a displacement of about 300 m in UK3D, with both faults displacing Permian rocks at outcrop.

The maximum normal throw on the Closehouse–Lunedale–Butterknowle fault zone, at the level of the top of the early Palaeozoic basement, is up to 5000 m (Chadwick et al., 1995); even within the 200–1000 m depth range of interest it remains a major fault with variable displacement greater than 200 m. Though a connection to a significant, deep-crustal structure seems likely, the currently available seismic reflection data reveal little evidence of such a relationship. Minor folding and reverse faulting in the hanging-wall block of the fault zone are evidence of some basin shortening and syndepositional folding, perhaps associated with dextral fault displacement (Burgess and Holliday, 1979; Kimbell et al., 1989; Chadwick et al., 1995).

The Lake District boundary fault zone marks the boundary of the East Irish Sea basin with the Lake District block; it also locally defines the western margin of the Lake District batholith (e.g. Evans et al., 1993, 1994; Akhurst et al., 1997). It is a large, north-north-west-trending structure traced over 65 km with a normal, down-to-west displacement varying from 320 to over 1800 m. North of Ravenglass, the fault zone divides into a network of synthetic and antithetic fault strands that affect Palaeozoic and Mesozoic strata in its hanging wall. The fault zone terminates at the St Bees fault zone (Akhurst et al., 1997).

South of Ravenglass, the Lake District boundary fault zone is narrow and interpreted as a single, west-dipping, normal fault. It juxtaposes the upper formations of the Sherwood Sandstone Group to the west against the Eskdale granodiorite, with a minimum throw of 1800 m, and corresponds to a sharp, linear residual gravity gradient. Farther south, near Bootle, it divides again, with the eastern strand continuing southwards as the Haverigg Fault (Dunham and Rose, 1941) to the Walney Channel near Barrow-in-Furness, and offshore into the Morecambe Bay area. This down-to-west, normal fault has a length of over 38 km and normal displacement of 320 m in UK3D, but may be up to 700 m (Rose and Dunham, 1977). The Lake District boundary fault zone has a long history of repeated reactivation, including the possibility of displacements as late as the Quaternary; kinematic indicators suggest a strong component of oblique slip on the zone (Akhurst et al., 1998).

The area north of Ravenglass is referred to as the Lakeland terrace, where a succession of less than 1000 m of older and younger cover rocks is preserved in the hanging wall of the Lake District boundary fault zone (Akhurst et al., 1997). The terrace is cut by many faults with relatively small throws and is cross-cut by north-east-trending faults. These include the Seascale–Gosforth fault zone, which transfers a significant proportion of the down-to-west displacement westward. It comprises a complex, mixed throw, braided, down-to-north (normal) fault zone, several faults of which are exposed in the early Palaeozoic basement to the east (Jackson et al., 1995; Akhurst et al., 1997). They include a number of named faults not in UK3D, including the Scale Beck, Guards and Rainors faults (the ‘Seascale–Gosforth fault zone’ in this study), the first of which has a throw of about 1000 m down to the north within the basement, but no expression in the cover rocks (Akhurst et al., 1997). Some strands were reactivated during Permo-Triassic times when they acted as a transfer structure, defining the northern margin of the Ravenglass sub-basin. The base of the Permo-Triassic succession is thrown down to the south across the fault zone with displacement increasing eastwards. However, understanding of the detailed fault structure is incomplete and the amount of displacement at the eastern end is very poorly constrained, although gravity data indicate a relatively abrupt step in this area (Kimbell, 1994). The Seascale–Gosforth fault zone is an important structure in the region but is not currently modelled in UK3D.

The easternmost strand of the Lake District boundary fault zone in the north is the arcuate Thistleton Fault, which throws down to the west, dividing the Borrowdale Volcanic Group into two stratigraphically and structurally distinct areas. Borrowdale Volcanic Group strata immediately west of the Thistleton Fault form a broad, easterly plunging syncline (Akhurst et al., 1997). The throw, down to the west, is not known, because strata in the hanging wall are not seen in the footwall. To the east, the Shepherd Crag Fault splays south-eastwards from the Thistleton Fault. It has a length of about 11 km and a throw of about 620 m in UK3D down to the west in the Borrowdale Volcanic Group. However, little effect is seen on the Ennerdale granite so it therefore is presumed to largely pre-date emplacement of the granite.

The St Bees fault zone at the northern end of the Lake District boundary fault zone is a complex, north-easterly trending plexus of *en échelon* faults with dominantly down-to-south displacements but with some down to the north, the geometry indicating a component of dextral, strike-slip movement. The fault zone becomes less continuous at shallower levels. The fault zone is aligned with the Causey Pike Fault and extends offshore, its mapped geometry indicating it may owe its origin to dextral reactivation of these basement structures into the younger rocks (Akhurst et al., 1997).

Strata of Palaeozoic and Mesozoic age are cut by the linked north-north-west Pennine and north-north-east Dent fault zones, which together form jagged, saw-toothed western boundaries respectively of the Alston and Askrigg blocks. The northern part of the Dent fault zone is referred to as the Dent line by Underhill et al. (1988). In turn, at the south-western corner of the Askrigg block, the Dent fault zone appears as a splay off the South Craven–Morley–Campsall fault system, forming a fundamental oblique-slip fault zone that dominates the block and basin architecture of Northern England (Corfield et al., 1996). The kinematics of the

Dent fault zone reflect north-north-west to south-south-east shortening and sinistral transpression during late Carboniferous Variscan deformation (Woodcock and Rickards, 2003; Thomas and Woodcock, 2015).

The Pennine fault zone is more than 70 km long and has an overall down-to-west, normal throw of at least 700 m. North of Gamblesby there is a single strand, but along the rest of the zone there are multiple, anastomosing, arcuate strands that together form a series of fault duplexes within which early Palaeozoic basement, older- and younger-cover rocks are preserved (Arthurton and Wadge, 1981; Burgess and Holliday, 1979). Individually named strands include, from north to south, the Deep Slack, Else Gill, Catterpallot, Fellside, Lounthwaite, Milburn, Dufton Pike, Knock Pike, Wharleycroft and Hilton faults, of which only the Lounthwaite, Milburn and Hilton faults are included at the scale of this dataset. The Swindale Fault is a splay linking the southern end of the fault zone with the Closehouse–Lunedale–Butterknowle fault zone. Details of these faults are given by Arthurton and Wadge (1981) and Burgess and Holliday (1970). The mapped geometries within the fault zone suggest that it is a flower structure, but a detailed interpretation of the kinematics is not currently available.

The Swindale Beck–Closehouse–Lunedale–Staindrop Fault is linked to the Hilton–Stainmore Summit Fault by the north-north-east trending Thornthwaite Fault, which has a mapped length of just under 5 km and downthrows to the east.

The Dent fault zone is a subparallel set of folds and near-vertical to steeply west-dipping anastomosing faults, together representing a major oblique-slip fault zone (Underhill et al., 1998; Aitkenhead, 2002). The fault zone marks the western margin of the Askrigg block and has a length of at least 31 km. The older cover rocks form an east-facing monocline comprising the Taythes Anticline and the Fell End Syncline: that structure is cut through by the steeply westward-dipping Dent Fault. Maximum throw on the faults is found in the south, where an easterly reverse downthrow juxtaposes Carboniferous and early Palaeozoic rocks. The amount of easterly downthrow decreases northward, such that westerly downthrow occurs along its northernmost extension. The throw down to the west on the Dent fault zone varies along its length between 600 and 1200 m, but diminishes abruptly north of the intersection with the Stockdale faults within the Askrigg block (Thomas and Woodcock, 2015). The hanging-wall block of the Dent Fault is cut by near-vertical or easterly dipping faults that, east of the Rawthey Fault, form a set of duplexes. Within these is the periclinal Taythes Anticline which resulted from reorientation of an earlier, Acadian fold. At its southern end, the Dent Fault converges with the north–south Barbon Fault and joins the Craven fault system (Thomas and Woodcock, 2015). The fault system represents an early Palaeozoic lineament, reactivated during Carboniferous and into Early Permian times, with oblique slip. It accommodated both the formation and north–south-directed shortening (inversion) of early Carboniferous basins and later (Triassic) north-east to south-west-directed extension, during the formation of the Vale of Eden half-graben, by oblique-slip movement along its length (Underhill et al., 1988; Aitkenhead, 2002). Younger movements may also have occurred but are difficult to document and are not thought significant.

North of the Stockdale faults the Dent line comprises two parallel, steeply dipping faults linked by north-east-trending faults. One of the main north-north-east-trending faults is overlain unconformably by Permian strata, indicating a pre-Permian age for displacement (Underhill et al., 1988). A westerly downthrow on the continuing Argill Fault grows northward to a maximum of about 700 m at its northern junction with the Augill Fault, preserving the Pennine Coal Measures Group strata in the Stainmore Monocline in the hanging wall (Burgess and Holliday, 1979; Thomas and Woodcock, 2015).

The intersection of the Dent, Pennine and Closehouse–Lunedale–Butterknowle fault zones is associated with tight folding and high-angle reverse faulting. The more plastic, older cover rocks responded initially by tight folding along axes parallel to the underlying faults, and then by the development of eastwards-facing monoclines with nearly vertical or overturned beds on the steep limb. For example, the Cotherstone Syncline (Figure 15) is a broad, easterly trending, asymmetrical structure with low dips on the southern flank, but steeper dips up to 20˚; to the north lies a tight anticline parallel to the Closehouse–Lunedale–Butterknowle fault zone.

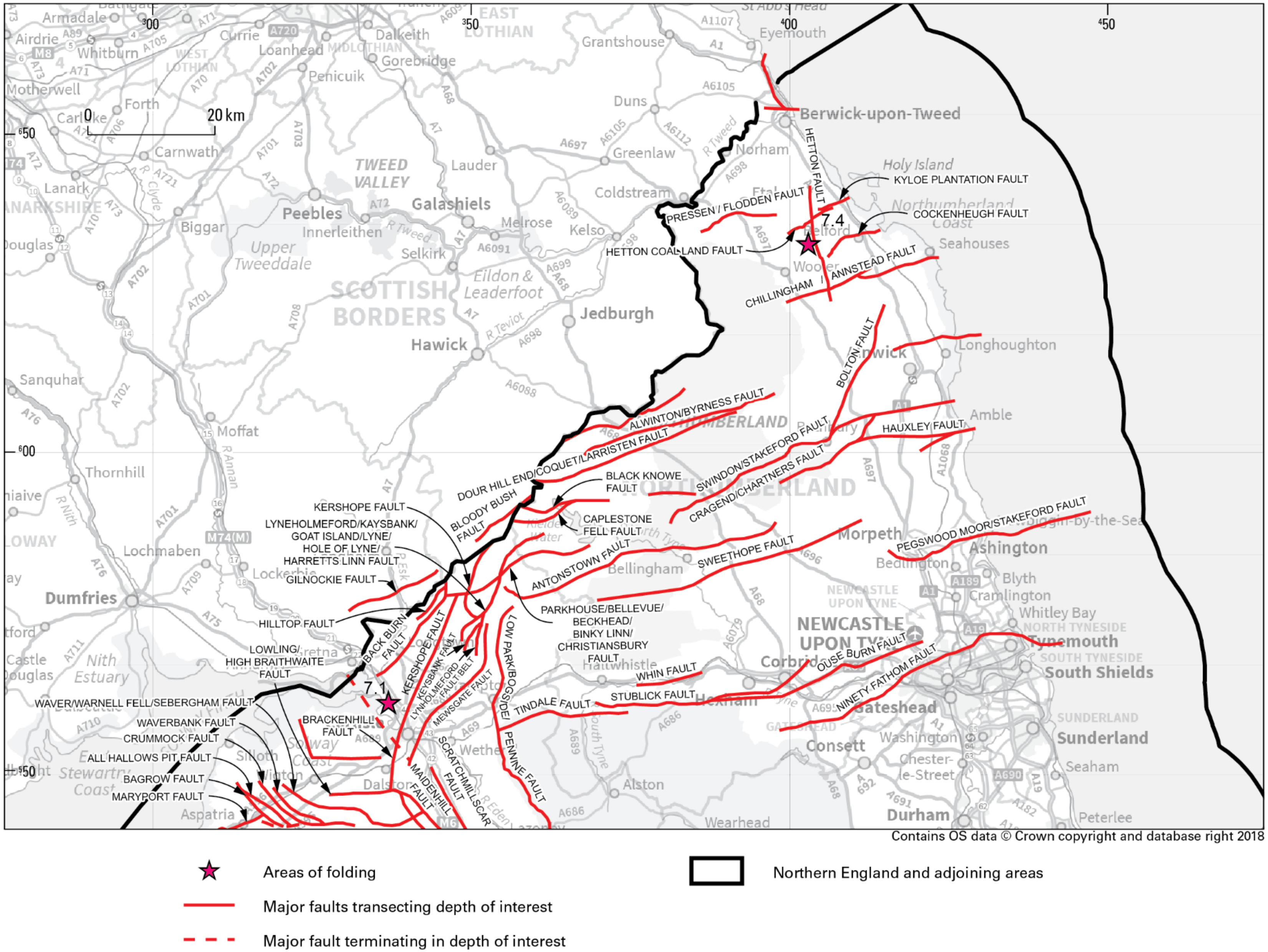

Figure 14 Regional map showing major faults and areas of folding in the north of the Northern England region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

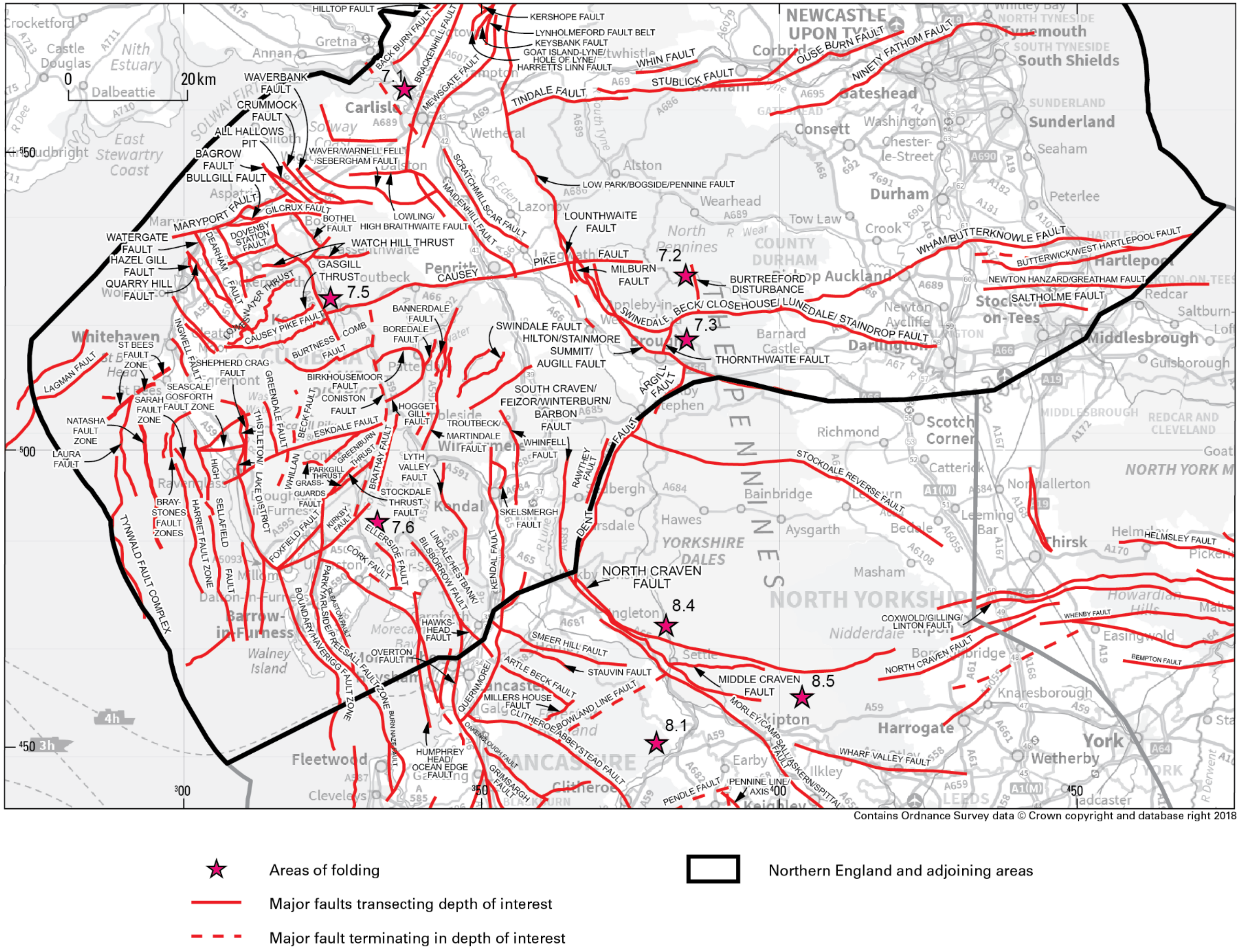

Figure 15 Regional map showing major faults and areas of folding in the south of the Northern England region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

5.3.1 Structures of the Palaeozoic basement rocks

The Lake District comprises the largest exposure of early Palaeozoic basement rocks in Northern England. Strata include up to 5000 m of turbiditic sandstone and mudstone (Early to Mid Ordovician Skiddaw Group), overlain in succession by volcanic rocks up to 6000 m thick (Late Ordovician Eycott and Borrowdale groups) and by at least 4500 m of sandstone and mudstone with subordinate limestone of the Windermere Supergroup (Late Ordovician and Silurian). The large-scale structure of these rocks is divided into four east-north-east-trending belts: a northern, north-facing, steep belt, referred to as the Cumberland Monocline; a central 'flat' belt cored by the Lake District batholith; a southern, south-east-facing steep belt, the Westmorland Monocline, and a southern 'flat' belt (Kneller and Bell, 1993; Woodcock and Soper, 2006; Stone et al., 2010).

The northern steep belt is dominated by the Eycott Volcanic Group outcrop, which dips steeply to the north. To the south of this, within the northern part of the underlying Skiddaw Group outcrop, are four major, approximately west–east faults: from north to south these include the Watch Hill, Loweswater, Gasgale and Causey Pike faults. Two distinct interpretations of these structures are summarised by Stone et al. (2010). The first interprets these structures as a set of thrust sheets that propagated southward ahead of the advancing Southern Uplands accretionary complex (Hughes et al., 1993). The second (Woodcock and Soper, 2006) models the structures as a deep-seated flower structure rooted along the northern margin of the Lake District batholith.

The Causey Pike Fault has a geographical extent that spans the Lake District inlier and extends as far as the Cross Fell inlier 30 km to the east. The fault has at least 2 km vertical throw down to the south, separating discrete parts of the stratigraphy with marked differences in sedimentary provenance and slump-fold orientation, indicating synsedimentary movement (Cooper et al., 2004). It also coincides with a major geophysical lineament (Lee, 1989) that is interpreted as a basement shear zone (Chadwick and Holliday, 1991) into which a concealed, approximately 400 Ma, elongated, granitic body (the Crummock Water granite (Cooper et al., 1988)) has been intruded.

A network of broadly north–south faults cuts across the Lake District. These faults are probably reactivations of pre-existing, basement fractures that propagated upwards during later deformation (Millward, 2002). The longer examples include, from west to east: the Greendale, Bannerdale, Boredale, Whillan Beck, Coniston, Brathay and Troutbeck faults, the last three of which produce significant offsets on the base of the Windermere Supergroup. These faults are subparallel to the Lake District boundary fault zone. Overall, the faults appear to have had synvolcanic displacement followed by Acadian reactivation; many also may have had a post-Acadian role, particularly during Permo–Carboniferous extension.

In the Wastwater area, the Whillan Beck and Greendale faults form a graben structure cutting the northern margin of the Eskdale pluton and adjacent Borrowdale Volcanic Group. The Whillan Beck Fault is about 17 km in length and has a westerly downthrow of 315–500 m, displacing the Eskdale granite contact by around 2 km (Millward et al., 2000). It is exposed on Rakehead Crag in a 30– 40 m-wide gully with intensely fractured, haematised rock. Displacement on the western, easterly downthrowing Greendale Fault is difficult to determine, but 315 m down-to-west displacement is indicated in UK3D.

The Coniston Fault is one of the most substantial fracture systems within the central Lake District, cutting through the Borrowdale Volcanic Group over a distance of some 40 km (Millward et al., 2000). It appears to be a simple, down-to-west, slightly arcuate, normal fault with over 225 m displacement in UK3D. North of Grasmere, the fault zone has a north-north-west trend but turns to a south-south-west trend in the south. At the head of Coniston Water, the fault zone is bounded to the east by the Waterhead Fault and to the west by the Ash Bank Fault. These two main strands are connected by numerous splays suggestive of sinistral, strike-slip movement. However, the system offsets the basal Windermere Supergroup unconformity dextrally by about 1.5 km, the main displacement being transferred northwards from the Waterhead Fault to the Ash Bank Fault along one of the north–south splays. Such contradictory evidence illustrates the complexity of likely polyphase fault movement.

Farther east, the Troutbeck fault zone is a 4 km-wide network of anastomosing fault strands extending for a length of more than 25 km (Millward, 2002). To the west of this structure, the volcanic strata are inclined eastwards, whereas those to the east are inclined westwards, bringing the Skiddaw Group to the surface in the Bampton inlier. The Troutbeck fault zone also follows the deep structural col established from geophysical data that separates the western and eastern parts of the batholith (Lee, 1989; Millward, 2002).

The Boredale and Bannerdale faults are subparallel and to the west of the Troutbeck Fault. The Boredale Fault has a length of approximately 6 km and downthrows to the west. The Bannerdale Fault has a mapped length of approximately 5.5 km and has a vertical, down-to-east displacement in UK3D in excess of 900 m.

East-north-east-trending faults in the Borrowdale Volcanic Group include the Burtness Comb, Birkhouse Moor, Hogget Gill, Langdale, Eskdale, Swindale, Grassguards, Stonythwaite and Bootle Fell faults (Millward, 2002; Johnson et al., 2001; Millward et al., 2000; Woodhall, 2000). Many of these have large, synvolcanic, normal displacements. For example, the Burtness Comb Fault extends from Buttermere to Ullswater and has a down-to-south throw of up to 2500 m. The Birkhouse Moor and Hogget Gill faults serve as linking structures between the Coniston and Troutbeck fault zones; displacements are between 150 and 500 m, controlling sedimentation within the volcanic succession. Similarly, the Grassguards Fault, with a throw of about 2 km down to the south, controlled preservation of volcanic successions to the south (Millward et al., 2000).

The Eskdale Fault extends from the coast around Ravenglass, possibly crossing the Lake District boundary fault zone in the west, and terminating in the east against the Coniston Fault a distance of about 29 km (Akhurst et al., 1997; Millward et al., 2000). The fault is locally associated with a zone of intensely fractured and haematised rock at least 100 m wide. The fault is exposed in the streams on the west and east sides of the summit of Hard Knott Pass and on the west side of Wrynose Pass, where displacement on the fault is about 70 m down to the north. Zones more than 50 m wide, of intensely fractured rock heavily stained with haematite, containing anastomosing seams of crush breccia, fault breccia, and gouge are exposed. Where the Eskdale Fault cuts the Eskdale pluton, crush zones form anastomosing networks locally, and adjacent north-north-west-trending fractures commonly contain haematite-cemented breccias. Mylonitic fabrics have been generated adjacent to the fault west of Brantrake Crags but no significant movement is evident. However, the fault is not currently accurately represented in UK3D. Vertical displacement of the early Palaeozoic rocks is small, but it is thought to have a dextral strike-slip displacement of 0.5–1 km, offsetting the Whillan Beck Fault.

The Borrowdale Volcanic Group was affected by volcanotectonic faulting; that is, faulting that was associated directly with magma movement. These faults are concentrated in the Scafell and Haweswater areas, associated with the explosive eruption of major silicic magma bodies and subsequent piecemeal caldera collapse (Branney and Kokelaar, 1994). The important characteristics of these faults are that they are local and segmented with spacings in the Scafell–Langdale area of 100–2000 m; the throws are of tens to hundreds of metres and the sense of displacement can change during the period of volcanism (Millward, 2002). Rotation of stratal dip and strike between adjacent blocks is commonplace (Millward et al., 2000).

Strata of the Windermere Supergroup and adjacent Borrowdale Volcanic Group in the southern Lake District dip steeply to the south-east and form the steep limb of the Westmorland Monocline (Kneller and Bell, 1993; Woodcock and Soper, 2006). Parallel and to the south of this zone lies the axial zone of the Bannisdale Syncline (Figure 15). The Westmorland Monocline has a maximum amplitude overall of about 10 km (Kneller and Bell, 1993). Acadian thrusts are developed in the steep limb of the Westmorland Monocline. These include the Greenburn, Stockdale and Park Gill thrusts, which are north-easterly trending and south-easterly dipping, and north-west-directed thrust faults, interpreted as backthrusts within the monocline by Kneller and Bell (1993). The Greenburn Thrust has a length of almost 8 km, but due to its nature, displacement is not well constrained or modelled in UK3D. It cuts out the common limb of an anticline–syncline fold pair within the Borrowdale Volcanic Group. The Park Gill Thrust occurs in the Coniston–Ambleside area of the Windermere Supergroup and ramps gently down sequence to the south-west. The Stockdale Thrust is a bedding-parallel detachment that only locally produces any stratigraphical offset and is difficult to recognise at outcrop, though it is shown across the inlier along almost the entire outcrop of the Stockdale Formation. Farther south-west, the thrust faults probably continue into the Ulpha Syncline as high-strain zones in the steeply dipping and north-north-east-striking strata. Cumulative displacement across the zone appears to be at least 4 km, with shortening of up to 70 per cent within the high-strain zones, which makes it difficult to discriminate between displacements that occurred on fault planes and the cumulative effect of shear. Thus, overall displacement may be considerably greater than the 4 km calculated (Millward et al., 2000). To the south and east and parallel to the thrusts are the Foxfield and Kirkby faults, which developed in accommodation to the folding within the area. Large sinistral movements are recorded along the faults with the Kirkby Fault having approximately 2.5 km (Johnson et al., 2001). The Kirkby and Foxfield faults may have been reactivated during the Carboniferous in dip slip.

North–south faults, subparallel to the Dent Fault and affecting rocks of the Windermere Supergroup include, from west to east: the Park, Bouth, Finsthwaite, Lyth Valley, Kendal, Skelsmergh, Whinfell and Barbon faults. In the Shap Fells, for example, faults of this orientation separate tracts with different fold patterns (Moseley, 1968), suggesting that the strain was partitioned by movement on the faults during folding.

5.3.2 Structures of the older cover cocks

The regional framework faults that define the boundaries of the blocks and basins structure exerted strong control on sedimentation, particularly in the early Carboniferous. Suites of faults with similar orientations to the framework exhibit a variety of orientations and evolutionary histories affecting the older cover rocks.

In contrast to its southern margin, the northern margin of the Northumberland–Solway basin is less clearly defined and is marked by an *en échelon* set of north-east-stepping, east-north-easterly trending faults including, among others, the North Solway, Gilnockie, Featherwood–Door Hill End–Coquet–Larristen, Cragend–Chartners and Hauxley faults. To the north of this line in north Northumberland lies the Cheviot block and the small Tweed basin. The block is underpinned by Devonian volcanic rocks and the Cheviot pluton; its northern margin is the Pressen–Flodden Fault (Kimbell et al., 1989).

East of the Cheviot Hills, on the eastern flank of the block, many east-north-east-trending faults affect the Carboniferous strata and are particularly well exposed on the coast. These have been described in detail by Shiells (1964) and de Paola et al. (2005), but are not currently well modelled in UK3D. Most have down-to-north, normal displacements of less than 150 m, but the Chilllingham–Annstead Fault has a displacement in the order of 300 m (Gunn, 1900). Examples of the minority of down-to-south, normal faults in this belt, which are around 10 km in length, include the Hetton Coal Law and Kyloe Plantation faults, which have up to 300 m of displacement and, to the south, the Cockenheugh Fault, with some 200 m displacement (Gunn, 1900). Also in this area is the north-north-west-trending Hetton Fault, a reverse, down-to-west fault with over 500 m displacement modelled in UK3D. The fault has removed the common limb of the Holborn Anticline to the east and the Lowick–Hetton Syncline to the west (Gunn, 1900; Shiells, 1964). A similar structure, the Bolton Fault, lies a little to the south and is associated with the Lemington Anticline.

South-west of the Cheviot Hills, towards Kielder Water, are the parallel, east-north-east-trending Alwinton–Byrness and Featherwood–Dour Hill End–Coquet–Larristen faults, each more than 30 km long, but these are not currently well modelled in UK3D. The geometry of the Alwenton–Byrness Fault is a poorly understood, down-to-south fault with a throw likely to be 100–200 m. It may have been reactivated with Variscan reversal linked to the northern margin of the Northumberland basin. To the south, the Featherwood–Dour Hill End–Coquet–Larristen Fault is a large, normal fault with a down-to-south displacement of over 1110 m in UK3D, although Chadwick et al. (1995) shows approximately 250 m displacement. To the south-west are the east-north-east to east–west-trending Black Knowe and Caplestone Fell faults. The Caplestone Fell Fault has a vertical throw of nearly 400 m in UK3D and the Black Bush Fault should have a similar displacement. The Black Knowe Fault is truncated by the Bloody Bush Fault to the west, which is a north-east trending structure similar to the Glinockie Fault to the south-west and may be the continuation of it.

En échelon to the south-east of the previous structure are the Swindon–Stakeford, Cragend–Chartners and Hauxley faults, which were active during early Carboniferous extension, although movements were smaller than on similar structures to the west (Lawrence et al., 2011). The Swindon–Stakeford Fault is a large, down-to-north fault, thought by Miller (1887) to have a displacement of some 800 m. However, seismic reflection data indicate that the downthrow to the north ranges from 200 to 400 m and is accompanied by complex, reversed faulting in its hanging-wall block, indicative of transpressive movements (Chadwick et al., 1995; Lawrence et al., 2011). It is not currently modelled in UK3D. The Cragend–Chartners Fault is an arcuate, normal fault with a displacement of at least 400 m down to the south (Lawrence et al., 2011). It is apparently offset by the Stakeford Fault, being displaced westwards across the fault to the north. The southern segment has a length of about 19 km, a displacement of 535 m in UK3D, and is linked to the Hauxley Fault. The Hauxley Fault is prominent at top early Palaeozoic basement, where the throw is almost 1200 m (Chadwick et al., 1995) and is also exposed on the coast at Hauxley Haven, where it has a down-to-south throw of about 290 m (Lawrence et al., 2011). Though the Hauxley Fault has a length of about 30 km it is thus one of the more important faults in Northumberland. A westward splay from the eastern part of the fault also has a southerly throw of approximately 390 m displacement in UK3D.

Farther south, in the central part of the Northumberland–Solway basin, several east-north-east-trending, normal faults are revealed on seismic reflection data, some of which show evidence of minor Variscan reversal (Chadwick et al., 1995). Examples of down-to-south faults include the Parkhouse–Bellevue–

Beckhead–Binky Linn Fault and the *en échelon* Antonstown Fault, whereas down-to-north faults include the Sweethope and Peggswood Moor–Stakeford faults. The arcuate Parkhouse–Bellevue–Beckhead–Binky Linn fault zone (also referred to as the East Christiansbury Fault by Chadwick et al., 1995) is some 25 km in length, with a displacement of over 300 m in UK3D. It comprises two main sections: the western Parkhouse–Bellevue and the eastern Beckhead–Binky sections. Day (1970) thinks displacement could increase eastwards to 600 m or more on the eastern section. The fault zone is offset by the Lyneholmeford–Kaysbank–Goat Island–Lyne–Hole of Lyne–Harriets Linn fault zone.

In the central part of the Northumberland–Solway basin, the Antonstown Fault and its antithetic Sweethope Fault, some 4 km to the south, form an important fault pair. The Antonstown Fault is a complex, sinuous, east-north-east-trending, down-to-south, normal fault, imaged on seismic lines and mapped at outcrop (Frost and Holliday, 1980). The fault has a length of about 46 km and a displacement of more than 200 m in UK3D. The Sweethope Fault has a length of about 44 km with a displacement of about 200 m (Chadwick et al., 1995). The Antonstown and Sweethope faults show evidence of minor Variscan reversal, with gentle upwarp of the hanging-wall block between the faults (Chadwick et al., 1995). *En échelon* to this is the Pegswood Moor–Stakeford Fault, about 15 km long onshore and extending offshore for another 17 km; it has a normal displacement down to the north greater than 230 m in UK3D. Evidence of minor Variscan reversal on the fault is also indicated by gentle, anticlinal flexuring of the hanging-wall block succession (Chadwick et al., 1995).

Along the Tyne valley, east of Haltwistle, the Whin Fault is a steep, down-to-south fault that is antithetic to the Stublick–Ninety Fathom Fault. It has a length of about 11 km and a normal displacement of up to 560 m in UK3D. It is closely associated with dolerite intrusions.

The Carboniferous of the north-west Lake District is cut by a major set of sometimes sinuous faults that have a north-west trend and throw down both to the north-east and south-west including from west to east the Ingwell, Hazel Gill, Quarry Hill–Mockerkin, Watergate, Dearham and Bothel faults. The faults typically terminate against the Maryport Fault in to the north. A few major cross faults, usually trending north-east or east and dominantly throwing down to the north, locally take up the main displacement from north-west-trending faults. It is likely that the two sets formed contemporaneously. There is little evidence of any major fold structures pre-dating faulting.

North-east of Carlisle is a complex set of subparallel, north-north-east-trending faults and related folds that extend for more than 60 km, which developed during early Carboniferous sedimentation in the area and then reactivated during Variscan events. The principal structures are the Back Burn, Brackenhill, Mewsgate and Goat Island–Lyne faults, the Solway Syncline and the Carlisle and Bewcastle anticlines. As much of this area is concealed by younger cover rocks, the geometry of these structures is known mostly from seismic reflection data (Chadwick et al., 1995), though the structure of the Bewcastle Anticline is described by Day (1970).

The Back Burn Fault is more than 20 km long and dips to the south-east; displacement on the top of the early Palaeozoic basement (at 2–3 km depth) is 1000 m, but middle Visean strata display a reverse throw of up to 800 m. Thus the fault was a normal, synsedimentary growth fault during early Carboniferous times, but was reversed during Variscan transpression. Parallel to this and defining the eastern margin of the Canonbie coalfield is the shorter Hilltop Fault, which is about 7 km long with a displacement of about 1490 m in UK3D.

The Brackenhill Fault marks the eastern margin of the Carlisle Anticline. It is a westerly dipping reverse fault more than 32 km long, which also shows a significant strike-slip component in its late Carboniferous movement. It was subsequently reactivated as a normal fault during Permian extension (Chadwick et al., 1995) but is not currently well modelled in UK3D. Inferred deformation of the base Permo-Triassic reflector near the Brackenhill Fault and, to a lesser extent, the Back Burn Fault may be due to Alpine compression or transpression (Chadwick et al., 1995). To the north of this, the Kershope Fault is about 14 km in length and has about 470 m of displacement in UK3D.

The Goat Island–Lyne Fault obliquely cuts the Bewcastle Anticline. The fault is an arcuate, steeply south-east dipping, down-to-west, reverse fault more than 25 km long (Day, 1970). Like many similar structures, the fault is associated with many other faults and small folds, and was formed by transpressive, reverse reactivation of an earlier synsedimentary normal fault (Chadwick et al., 1995). The Mewsgate Fault (the ‘Crosby Fault’ of Trotter and Hollingworth, 1932) is about 27 km long and appears to be a north-westerly dipping, reverse fault.

On the Alston block, the north–south Burtreeford disturbance is a faulted, eastwards-facing monocline that has a vertical displacement of about 150 m in UK3D. At its northern extent its displacement is divided among a splay of mineralised fractures and a down-to-west normal fault just to the west of Allenheads (Dunham, 1990). Though most of the faults and mineralised fractures in the north Pennine orefield have displacements generally of only a few tens of metres (Dunham, 1990), the west-north-west-striking 'Quaterpoint' veins have characteristics suggestive of transtensional fault movements (Critchley, 1984). One of these structures, the Slitt Vein, was the site in Weardale of geothermal energy exploration (Manning et al., 2007; Younger and Manning, 2010).

In the southern Lake District, the north–south faults that were initiated earlier in the Acadian Orogeny mark the boundaries of small sub-basins in the Carboniferous. The main example here is the down-to-west, Kendal–Quernmore Fault, which in UK3D is mapped over 49 km into the adjacent Pennine region to the south. It has a normal displacement of over 350 m. It is not well imaged on seismic reflection data, but in the south it is associated with an east-facing monocline at surface, suggesting Variscan reversal of a down-to-west, normal fault (Brandon et al., 1998; Kirby et al., 2000). The structures are associated with a north-trending gravity gradient. Its origin is uncertain and both normal (down-to-west) and reverse (down-to-east) net displacements are possible. Other north–south-trending faults in the area include the Lyth Valley, Skelsmergh and Whinfell faults having lengths of 20, 6 and 16 km respectively. All except the Whinfell Fault downthrow to the west.

5.3.3 Structures of the Permo-Triassic and Early Jurassic outcrops

Permian and Triassic strata crop out in Northern England west of the Pennines, around Carlisle; in the Vale of Eden, in west and south Cumbria, and east of the Pennines over much of County Durham. The Vale of Eden and Carlisle basins formed separate depocentres during Permian times, with seismic reflection data indicating that the Penrith Sandstone Formation in the Carlisle basin is not physically connected to the outcrop in the Vale of Eden (Stone et al., 2010). The 15 million years of erosion following Variscan deformation is illustrated by the relatively smooth, peneplained, basal Permian surface imaged on seismic reflection profiles in the Carlisle basin (Chadwick et al., 1995). Much of the control on subsequent Permian to Jurassic sedimentation was through extensional reactivation of established fault zones (Stone et al., 2010). Jurassic strata are known only in a small outlier of approximately 70 km^2 within the Carlisle basin, where they are faulted against Mercia Mudstone Group strata to the north, south and west.

The Permo-Triassic outcrop in the Vale of Eden is preserved within a north-west-striking half-graben, separating the Lake District and Alston blocks. The structure was controlled at the eastern margin by westerly, normal downthrow on the Pennine fault zone (Shotton, 1935; Burgess and Holliday, 1979; Arthurton and Wadge, 1981). However, there is no seismic reflection or borehole information to define the detailed geometry of the basin. In the north of the Vale of Eden, the western margins of the half-graben are affected by north-north-west-trending faults, including the down-to-west Scratchmillscar and Maidenhill normal faults. The Scratchmillscar Fault is about 22.5 km in length and displaces Permian rocks by about 50 m, but also has about 100 m of pre-Permian throw. The Maidenhill Fault has a length of over 26 km, with 10–15 m displacement of Permo-Triassic rocks but to the north, the throw is much greater in the Carboniferous rocks, being estimated at about 350 m near High Head (Arthurton and Wadge, 1981). The fault merges with the Lowling–High Braithwaite–Roe Beck East Fault that forms part of the Maryport–Stublick–Ninety Fathom fault zone.

To the north of Carlisle, the north-north-east Backburn–Hilltop, Brackenhill and Mewsgate faults, which controlled Carboniferous sedimentation in the area, also displace Permo-Triassic strata. A westerly normal downthrow of up to 400 m on the base of the Permian strata across the Brackenhill Fault resulted from extensional reactivation of that structure (Chadwick et al., 1995).

North-north-west-trending faults in the coastal area of west Cumbria and south of the Lake District block are parallel to the Lake District boundary fault zone and relate to the development of the major Permo-Triassic depocentre offshore in the East Irish Sea. Numerous smaller, north-west to south-east faults, in some places linked with west–east faults, occur throughout the area; most have south-westerly downthrows. Exceptionally, the downthrow is in the opposite direction, producing fault graben, the positions of some appearing to have influenced subsequent haematitisation (Rose and Dunham, 1977). A number of the larger faults extend southward into the adjacent Pennine region.

The Park–Yarlside–Gleaston–Preesall Fault to the east of the Lake District boundary fault zone forms a braided set of arcuate, down-to-west, normal faults. The northern segment, the Park Fault, which forms the boundary between the early Carboniferous and early Palaeozoic rocks, is a linked system of fractures and has a substantial but poorly constrained displacement (Rose and Dunham, 1977). The Yarlside Fault dips west at about 60˚ and has a throw estimated at not less than 450 m (Rose and Dunham, 1977), but up to 1030 m in UK3D. The southern segment, the Preesall Fault, with a length of about 22 km and displacement of about 970 m in UK3D, defines the eastern boundary to the Preesall salt field onshore to the west of Blackpool (Wilson et al., 1990).

The Stone Cross–Ellerside–Cark–Humphrey Head faults comprise both northerly and north-westerly trending segments that throw down to the south-west; they extend southwards across Morecambe Bay (Johnson et al., 2001). The Ellerside segment is a sinuous, north-west-trending fault about 8 km long and is seen only to juxtapose Carboniferous strata against early Palaeozoic basement. Around Allithwaite, it merges with the north-west to south-east Cark Fault, which is at least 9.5 km long and has more than 450 m of displacement in UK3D. Lying about 2.5 km to the south is the Stone Cross Fault, more than 19 km long and with greater than 210 m displacement in UK3D. These faults join the north–south-trending, normal, down-to-west Humphrey Head Fault, which is almost 23 km in length and has over 750 m of displacement in UK3D.

Farther east, the Lindale–Hest Bank–Bilsborrow–Grimsargh fault zone is a north-north-westerly trending, *en échelon* set of down-to-west faults (Jackson et al., 1995; Akhurst et al., 1997; Aitkenhead et al., 1992; Johnson et al., 2001). This fault zone also extends southwards into the adjacent Pennines region. The northern segment, the Lindale–Hest Bank Fault, is about 50 km long and throws down to the west, although the amount of displacement is not available in UK3D. To the south, the western, *en échelon* Bilsborrow Fault is about 30 km long, throwing down to the west and forming the boundary between the younger and older cover rocks in the south of the region, with up to 430 m displacement indicated in UK3D. The down-to-west Grimsargh Fault splays off south-east from the Bilsborrow Fault and in part defines the eastern edge of the Permo-Triassic outcrop, although its precise location is conjectural because of thick superficial cover and sparsity of borehole data (Aitkenhead et al., 1992). It is mapped over a distance of about 20 km and has a normal displacement of younger cover rocks estimated to be about 230 m. To the west, the Overton Fault has a similar trend but with an eastwards direction of downthrow, defining the western extent of the Permo-Triassic outcrop in the Torrisholme basin. The amount of downthrow is likely to be in excess of 100 m. The Hawkshead Fault is inferred to trend north-west to south-east to account for the marked change in the strike of the Pendle Grit Member and adjacent (Tournaisian/Visean) limestones around Stub Hall and is either a splay to the Lindale–Hest Bank–Bilsborrow–Grimsargh fault zone or terminates against it. The fault is approximately 8.5 km in length and downthrows to the south-west.

The Ocean Edge Fault can be traced northwards across Morecambe Bay, east of the Morecambe Bay tidal barrage site investigation to the Humphrey Head Fault in Cartmel, forming a combined fault zone of length in excess of 22 km. It marks the boundary between the Carboniferous and Triassic rocks and throws to the west

Offshore, a number of large, parallel to subparallel, north–south trending structures are synthetic or antithetic to the Lake District boundary fault zone. These include from, east to west: the High Sellafield, Sarah, Harriet, Braystones, Natasha, Laura and Tynwald faults. The High Sellafield fault zone is interpreted to be a continuous structure with normal, down-to-east displacement at depth and a series of *en échelon* structures consistent with a component of sinistral strike slip (Akhurst et al., 1997). The Natasha fault zone is a normal fault dipping moderately to the east, with a well-developed rollover that may have a wide zone of antithetic and synthetic faulting in its hanging-wall block. It has an overall maximum throw down to the east of 650 m with considerable oblique displacement (Akhurst et al., 1997). The Laura fault zone has an overall maximum normal downthrow to the east of 600 m, with a significant component of oblique slip (Akhurst et al., 1997). The Harriet fault zone has an unusually complex geometry. At the base of the Permo-Triassic sequence it is a single, down-to-west step but at higher structural levels it becomes a complex zone of synthetic and antithetic faulting up to 4 km wide; it includes an open anticlinal structure with a collapse graben at the fold crest (Akhurst et al., 1997). The arcuate Braystones fault zone comprises several component structures with cumulative throw down to the east and locally developed minor folding in the hanging-wall block, (Akhurst et al., 1997). It links southwards into the Sarah fault zone, which is a probable low-angle, listric, normal fault (Akhurst et al., 1997).

In the south-east of the region, in County Durham and Teesside, Permo-Triassic rocks crop out across the northern areas of the eastern England platform with an average regional dip of 1.25˚ to the east; locally it is steeper in the vicinity of major west–east faults. These include the Butterwick–West Hartlepool, Newton

Hanzard–Greatham and Saltholme faults, parallel to the Wham–Butterknowle Fault. The Butterwick–West Hartlepool Fault is over 36 km long, with a throw down to the south of almost 300 m. It extends about 20 km offshore where it joins the Wham–Butterknowle Fault. The Newton Hanzard–Greatham Fault has a length of about 38 km, extending some 17 km offshore into the North Sea and also throws down to the south with a displacement of about 1000 m in UK3D. The Saltholme Fault has a length of about 8 km and a displacement of about 1125 m in UK3D, mostly to the south; it was originally a down-to-south, normal fault with some Variscan inversion and was then reactivated again as a normal fault during the Permo-Triassic.

5.4 FOLDING

Areas where folding is considered to be a notable feature in the region are highlighted in Figures 14 and 15. These areas, potentially comprising multiple structures, are described in addition to named fold structures that occur in other parts of the region and are often directly associated with faults.

Folding in the region is related to the Acadian Orogeny (affecting only the basement) and to the far-field effects of the Variscan and Alpine orogenic phases resulting in:

- gentle, open folds affecting the younger cover, most notably in the Solway basin
- tighter folding affecting older cover rocks and generally associated with underlying reactivated and reversed early Carboniferous syndepositional normal faults; occurs mainly in the Solway and Northumberland areas and associated with the Pennine Fault/Dent line
- folding and cleavage developed in the early Palaeozoic basement rocks of the Lake District and Cross Fell inliers

Within the Skiddaw Group, early deformation was a syndepositional, soft-sediment, slump-related phenomenon, culminating in olistostrome development in late Arenig to early Llanvirn times (Webb and Cooper, 1988; Hughes et al., 1993). The Skiddaw Group was uplifted, probably faulted and eroded in Late Ordovician times, prior to volcanism, forming the unconformity beneath the base of the volcanic rocks, however, there is no evidence of folding and cleavage imposition at this time (Millward and Molyneux, 1992). Subsequent polyphase deformation and cleavage development was related to the Acadian Orogeny (Early Devonian); east-north-east-trending folds with amplitudes and wavelengths of several kilometres developed including the Sale Fell, Scawgill, Barf and Skiddaw anticlines and the complementary Wythop and Dodd synclines (Cooper et al., 2004). These are mostly tight to isoclinal structures with steeply inclined to vertical axial planes and gently plunging hinges.

Three large synclinal structures, the Scafell, Haweswater and Ulpha synclines of Soper and Moseley (1978) dominate the Borrowdale Volcanic Group. The previously identified anticlines at Wrynose and Nan Bield (Soper and Moseley, 1978) have been subsequently shown to be bedding strike and dip rotations across faults and not true folds, reinforcing their interpretation as volcanic structures (Millward et al., 2000). The Haweswater Syncline is much broken up by faulting, but the Scafell Syncline is a well-defined, east-north-east-trending, closed basin structure in the central Lake District, west of the Coniston Fault. The Scafell and Haweswater synclines are interpreted as major piecemeal calderas (Branney and Kokelaar, 1994; Millward, 2002). The Ulpha Syncline in the south-west is truncated by the unconformity at the base of the Windermere Supergroup, but began as a major volcanic depocentre controlled by displacement on the Grassguards Fault. All three were subsequently tightened during Acadian deformation (Millward et al., 2000).

In the south-west of the Lake District, the Black Combe antiform is a volcanotectonic fault block modified into a north-east-plunging fold during Acadian deformation (Johnson et al., 2001). South-east of the axial zone of the Bannisdale Syncline, Windermere Supergroup rocks form a series of folds with styles varying from tight to open, alternating with rolling strata in which the enveloping surface is subhorizontal. In the Furness district, larger structures include the Rebecca Syncline and Lowick and Stewnor anticlines (Johnson et al., 2001). These trend and plunge north-east and form a complex anticlinorial structure. Numerous other small and medium-scale folds are also present, and are particularly well developed on the northern limb of the Lowick Anticline, where they have a half wavelength of several hundred metres. The intervening synclines have been cut by thrust faults. At higher structural levels, the amount of subsidiary folding decreases, with most of the small and medium-scale folds dying out within the more competent sandstone formations.

In the east of the Lake District, the Carlingill Anticline and complementary Castley Knotts Syncline are major folds with hinge zones 4–5 km apart containing homoclinal limbs as much as 2 km in cross-strike width (Millward et al., 2010). The folds comprise zones of multiple, gently plunging hinge zones at least

1000 m wide. The wavelength of subsidiary folds is between 100 and 500 m. Two particularly large subsidiary folds are the west-plunging Farfield Syncline and Winder Anticline. The axial planes of these folds are nearly vertical.

A single Acadian cleavage is developed throughout the early Palaeozoic rocks as a penetrative, mica-defined fabric in the mudstones and as a more widely spaced, pressure-solution fabric in sandstone and coarser volcanic rocks. The cleavage is generally steeply inclined (though strongly refracted through different lithologies) but has a less arcuate strike trend than the axial planes to the many folds. Hence, the cleavage shows a small clockwise transection of the fold hinges in the west of the outcrop, passing eastwards into a small anticlockwise transection (Soper et al., 1987). This is part of a wider pattern of transecting cleavage seen across the early Palaeozoic strata of Britain and Ireland (Woodcock and Soper, 2006).

The major Carboniferous folds of the region lie within the Solway basin, which appears to have been more strongly inverted than the Northumberland–Solway and Stainmore basins (Chadwick et al., 1995). The pattern on the Alston and Lake District blocks was one of gentle warping and tilting. Over the former, Carboniferous rocks form a gentle, open, periclinal fold with an approximately west–east axis, referred to as the Teesdale dome (Figure 15; Location 7.2; Dunham, 1990).

The main group of north-north-easterly trending folds includes the Solway and Oakshaw synclines, the Carlisle, Routledge Burn, Stapleton and Bewcastle anticlines and the Back Burn Monocline (Figure 15). All folds are associated with reversal of underlying, early Carboniferous, syndepositional, normal faults and a number show much of the Carboniferous sequence removed along their axes during Early Permian erosion (e.g. the Carlisle Anticline (Chadwick et al., 1993)).

In north Northumberland, east of the Cheviot massif, Carboniferous rocks form two asymmetrical anticline–syncline pairs, each 18 km long and 2.5–5 km across, the common limbs of which are cut by high-angle, reverse faults (Figure 14; Shiells, 1964). The northern of the two structures, the Holborn Anticline and its complementary Lowick–Hetton Syncline to the west, along with the associated Hetton Fault, trend north-north-west. To the south, the Lemmington Anticline and the Bolton Fault trend north-north-east. Farther north, and in contrast to these structures, the north-north-westerly trending Berwick Monocline faces east (Shiells, 1964). This structure can be traced for at least 14 km before it dies out southwards, but north of Berwick-upon-Tweed the steep limb is a high-angle, reverse fault, juxtaposing steeply dipping, older cover rocks against Silurian and Devonian strata. Smaller-scale, periclinal folds affect early Carboniferous strata in this region (Shiells, 1964).

The Carboniferous rocks of the Vale of Eden were folded into a broad, shallow, north-westerly plunging syncline, which was modified to the south by minor anticlines and synclines with a general north–south axial trend (Arthurton and Wadge, 1981; Burgess and Holliday, 1979). In the east the syncline is truncated by the Pennine fault zone.

In the south of County Durham, the west–east-trending Trimdon Anticline and its complementary syncline to the south affect older cover rocks, much of which were eroded from the axial region of the structure prior to deposition of Permian strata in the area. The anticline is asymmetrical, with a steep northern limb, and developed in the hanging wall of the reactivated Butterknowle Fault, which marks the southern margin of the Alston block. Farther north in County Durham, Pennine Coal Measures Group strata form a broad, irregular, south-east-trending and plunging structure referred to as the Boldon Syncline. Strata of the Pennines Upper Coal Measures Formation are preserved in the axial region. Offshore in the Durham and Northumberland coalfield the Vane Tempest structure is a north-north-west-orientated, asymmetrical anticline with a steep, south-western flank (Jones et al., 1980).

In addition to the gentle, sag-like, open folds associated with the Permian and Mesozoic strata in the main depocentres, general eastward tilting and uplift of the region occurred in Cenozoic times, as a consequence of thermal doming associated with the opening of the North Atlantic Ocean to the west and subsidence of the North Sea basin to the east; this is a process that probably continues today (Chadwick et al., 1994).

5.5 REGIONAL DYKE SWARMS

Igneous dyke swarms of Ordovician, late Silurian to Early Devonian, late Carboniferous to Early Permian, and Palaeogene age are known at the surface and in the subsurface across the region. Whilst many are not emplaced along faults, they are described here because they have the potential to form conduits for fluid flow across stratigraphical boundaries.

The Ordovician and late Silurian to Early Devonian suites cut the early Palaeozoic strata in the Lake District, Cross Fell, Cautley, Dent and Teesdale inliers and in the Cheviot block (Stone et al., 2010). Late Carboniferous to Early Permian dykes comprise the east-north-east-trending dykes of the Northern England tholeiitic dyke swarm, which is associated with, and probably were feeders to, the Whin Sill swarm underlying about 4500 km^2 of Northern England. They extend from the southernmost outcrops in Lunedale, west as far as the Pennine escarpment, and north to Holy Island (Stone et al., 2010).

The dyke swarm occurs in four, widely separated dolerite subswarms, three of which could be regarded essentially as discontinuous single dykes with *en échelon* offsets (Johnson, 1995; Stone et al., 2010). They include the Holy Island, High Green, St Oswald's Chapel and Hett subswarms. The Holy Island subswarm is a set of dextrally offset dykes lying at the northern margin of the Cheviot block. South of the Cheviot Hills, the High Green subswarm was emplaced within the Swindon and Cragend–Chartners faults and is traced for over 80 km, crossing the coastline at Boulmer. The St Oswald's Chapel subswarm shows broadly sinistral offsets and includes the Haltwhistle, Erring Burn, Bavington and Causey Park dykes, the last of which can be traced for some distance offshore from Druridge Bay. Near Hexham, this subswarm swings more north-easterly, converging towards the High Green subswarm. Finally, near the southern margin of the Alston block, the Hett subswarm comprises several dykes, including the Brandon and Ludworth dykes (Smith and Francis, 1967).

Palaeogene dykes in the region comprise an *en échelon* suite of east-south-east-trending, mafic dykes, the largest and best known of which are the Cleveland–Armathwaite and Acklington dykes. The former extends from Cumbria into Yorkshire (e.g. Mills and Hull, 1976; Arthurton and Wadge, 1981) and can be traced on the aeromagnetic map of Great Britain across the Solway Firth to link with the Palaeogene igneous complex of Mull. It also extends south-eastwards into the Eastern England region in the Tees Valley and can be followed south-eastwards in a series of *en échelon* outcrops for about 50 km to Fylingdales Moor (Milsom et al., 2006). The dyke is 20–35 m wide within the region, with inclined lenticular sills thought to connect some overlapping components. The Acklington dyke crops out in north Northumberland.

5.6 UNCERTAINTY

Faults are planes of movement along which adjacent blocks of strata have moved relative to each other. They commonly consist of zones, perhaps up to several tens of metres wide, containing several to many fractures and zones of intense fracturing, brecciation or fault gouge. The portrayal of such faults as a single line on the geological map is therefore a generalisation. Faults are only rarely seen at outcrop, but their presence, attitude and location may be inferred or interpolated from geological mapping of offset formational boundaries. The degree of confidence in the location and character of the structures is at least in part dependent upon the nature and degree of confidence in mapping those adjacent formations at outcrop. Geological mapping in areas of high topographical relief such as the Lake District provides a three-dimensional understanding of the structural geometry in the shallow subsurface. A wealth of data on the location and geometry of some faults, to the limit of the depth of mining, is provided by seam plans in the main coalfields and by mine plans where mineralised faults have been worked.

The presence, subsurface location, attitude and displacement of faults may be determined by geophysical techniques. These techniques carry varying degrees of confidence, depending on their degrees of sensitivity and thus resolution. Potential field (gravity and aeromagnetic) data are the least sensitive techniques on which to base interpretations, with structures identified and mapped tending to be larger scale. Seismic reflection data provide greater resolution and thus permit more accurate identification, location and mapping of faults and other structures in the subsurface. Areas where there is limited or no seismic data thus carry the greatest degree of uncertainty.

Seismic reflection data coverage for the region varies in both the density and quality of data, in part related to the vintage of differing surveys but also to the prospectivity of the subsurface strata. The best coverage is across the Northumberland–Solway basin, and is of equal density over both the younger cover and older cover outcrops. A zone of poorer coverage in the region of the Mewsgate–Goat Island–Lyne faults separates the two areas. Elsewhere, seismic reflection data have been acquired over the eastern ends of the Stainmore basin and the Permian and Triassic rocks of the Darlington–Middlesbrough area, extending from the adjacent Eastern England region

Seismic coverage in the coalfields (West Cumbria, and Durham and Northumberland) is sparse to absent. There is no seismic coverage over the Cheviot, Alston and Lake District blocks, except for detailed coverage in the Sellafield area, where data were acquired for previous radioactive waste repository investigations.

Principal uncertainties in seismic location depend on the spacing and quality of the seismic grid, migration (or not) of the data and depth conversion of the interpretation. Experience shows that under good conditions, uncertainty of XY location should be better than 50 m; Z depth uncertainty at 1000 m, about 50 m; and smallest recognisable vertical offset, about 20 m.

6 Screening topic 3: groundwater

6.1 OVERVIEW OF APPROACH

This section explains what is known of shallow and deep groundwater flow regimes in the Northern England region, the regional groundwater flow systems, and any units or structures that may lead to the effective separation of deep and shallow groundwater systems including evidence based on groundwater chemistry, salinity and age. It describes the hydrogeology of PRTIs (or their parent units), principal aquifers and other features, such as rock structure or anthropogenic features (including boreholes and mines), that may influence groundwater movement, and interactions between deep and shallow groundwater systems. It also includes a note on the presence or absence of thermal springs (where groundwater is >15º C) that may indicate links between deep and shallow groundwater systems.

The groundwater DTI (RWM, 2016b) describes how the information on groundwater relevant to the NGS exercise has been prepared. Unlike the rock type, rock structure and resources screening attributes, there is no systematic mapping of relevant groundwater-related parameters across the region and there is typically very little information available for the depth range of interest (200 to 1000 m below NGS datum). What information is available on regional groundwater systems from the peer-reviewed literature is usually focused on the depth range of active groundwater exploitation, i.e. largely above the depth range of interest. In addition, groundwater movement and chemical composition can vary significantly over short lateral and vertical distances even in the depth range of interest. Consequently, uncertainty in our understanding of groundwater systems in the depth range of interest is high, and it will be important to develop a detailed understanding of groundwater movement and chemistry and their implications for a safety case during any future siting process or site characterisation (RWM, 2016a).

A few basic groundwater-related concepts have been used in the screening exercise. These include the term ‘groundwater’, which is used as defined by the Water Framework Directive (2000/60/EC) (European Union, 2000) as ‘all water which is below the surface of the ground’. An ‘aquifer’ is a body of rock containing groundwater, and a ‘principal aquifer’ is a regionally important aquifer and is defined by the Environment Agency as ‘layers of rock that have high intergranular and/or fracture permeability, meaning they usually provide a high level of water storage’ (Environment Agency, 2013). To date, the extent of principal aquifers have been mapped onshore only. Aquifers, PRTIs and rock structures such as faults may have relatively high or low permeabilities, i.e. they may transmit groundwater more or less easily. A description of the terminology can be found in the groundwater DTI (RWM, 2016b). Depending on the permeability of a rock sequence, groundwater flows from recharge areas (areas of aquifer exposed at the land surface and receiving rainfall) through saturated aquifers and, typically, on towards discharge areas, such as river valleys or along the coast. Overviews of how regional groundwater flow systems form and what controls their behaviour can be found in hydrogeological text books such as Freeze and Cherry (1979).

6.2 GROUNDWATER SYSTEMS IN NORTHERN ENGLAND

The regional groundwater flow systems in Northern England are conceptualised as being controlled by the broad distribution of geological units and the regional geological structure; the hydrogeological characteristics of those units; topography and the distribution of recharge, and other hydraulic boundary conditions imposed by the coastlines with the North Sea and Irish Sea to the east and west of the region respectively and by the major rivers across the region, such as the rivers Eden, Tyne and Tees.

The generalised vertical section (GVS) for the Northern England region (Table 3) divides rock units into three broad lithostratigraphical systems: Devonian and older basement rocks, older sedimentary and igneous rocks (Carboniferous to early Permian) and younger sedimentary rocks of Permian to Jurassic age. Rocks of all three lithostratigraphical systems can be found at outcrop within the region.

The region comprises a series of depositional basins divided by structural blocks that generally form higher ground and that are an important focus for recharge to the regional groundwater systems. Early Palaeozoic rocks are typically exposed in these fault-bounded blocks. The five principal aquifers in the Northern England region (Figure 16) are primarily preserved in the depositional basins and are:

- the Triassic Sherwood Sandstone Group
- the Permian Appleby Group (including the Penrith Sandstone**,** Brockram and Collyhurst Sandstone formations)

- limestones and dolomitic limestones within the Permian Zechstein Group
- the Permian Rotliegendes Group
- the Carboniferous Fell Sandstone Formation

All, except the dolomitic limestones of the Zechstein Group, are in the depth range of interest. Note that other aquifers crop out across much of the region (Figure 16), including many formations within the Carboniferous Yoredale, Millstone Grit and Border groups. Although locally important, with the exception of the Fell Sandstone Formation, they are not classified as principal aquifers and are not discussed further in this report.

Groundwater flow in the aquifers in each of the basins is a function of the specific basin recharge and boundary conditions. For example, in the Sherwood Sandstone Group in the Carlisle basin, groundwater flow is towards the centre of the basin (Allen et al., 1997). In the southern part of the basin, groundwater flows towards the north-west and discharges as river baseflow and to springs. In the east of the basin, groundwater flow is to the west, with some discharge to rivers (Daily et al., 2006a; Allen et al., 1997).

In west Cumbria, in the Sherwood Sandstone Group, recharge generally occurs in areas of higher ground in the east, and flows through the sandstone aquifers to discharge in the west into streams, rivers and the sea, and locally to springs (Allen et al., 1997). Flow is subhorizontal on a regional scale, due to the low vertical permeability of the St Bees Sandstone Member of the Chester Formation (formerly the St Bees Sandstone Formation, and referred to as such in much of the literature widely used in the references here). Away from recharge areas there is a general upward hydraulic gradient, enhanced by the anisotropy of the sandstone aquifer system (Allen et al., 1997).

In the Vale of Eden, Downing et al. (1987) indicates that the main direction of flow in the Permo-Triassic aquifer (largely comprising the Permian Appleby Group) is towards the north-west. Daily et al. (2006a) and Allen et al. (1997) state that groundwater flow in the aquifer in the Vale of Eden is dominated by flow to the River Eden. Allen et al. (1997) states that hydraulic gradients in the Penrith area are shallow and predictable, generally towards the rivers Eamont and Eden. Groundwater can be transferred laterally into the Penrith Sandstone Formation from the Carboniferous Limestone Supergroup where the Permian aquifer directly overlies the Carboniferous to the south of Penrith (Allen et al., 1997).

East of the Pennines, groundwater flow in the Zechstein Group aquifer (formerly referred to as the Magnesian Limestone) is predominantly along fracture systems, which may be preferentially oriented north-north-west and north-north-east (Atkinson, 2004). Groundwater flow to the north of the West Hartlepool Fault is eastwards, discharging to the sea, while south of the fault flow is south-eastwards towards the River Tees, which is a potential focus for groundwater discharge (Atkinson, 2004). Numerous faults cut the limestones: in some cases they may act as partial barriers to flow and in others they form high flow zones (Atkinson, 2004).

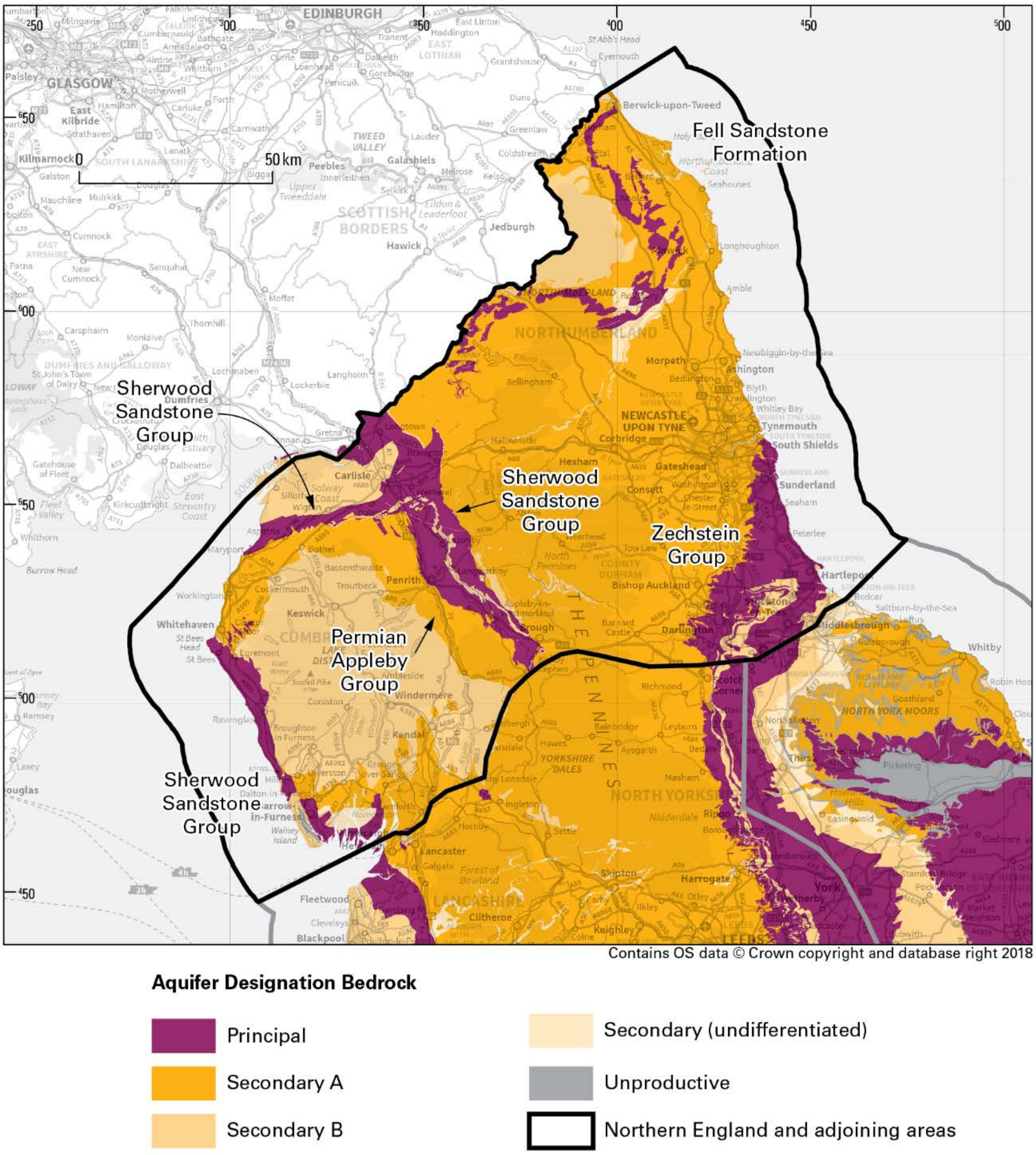

Figure 16 Location of onshore bedrock principal and secondary aquifers at outcrop in the Northern England region. The principal aquifers are the Triassic Sherwood Sandstone Group; the Permian Appleby Group (Penrith Sandstone, Brockram and Collyhurst Sandstone formations) and the Rotliegendes Group (not shown); limestones and dolomitic limestones within the Zechstein Group; and sandstones in the Carboniferous Fell Sandstone Formation. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

Regional groundwater flow in the Fell Sandstone Formation in Northumberland is likely to be down dip towards the south-east, through fractures and fissures, but aquifer heterogeneities — particularly faulting and discontinuous aquifer layers — may lead to locally different flow patterns (Environment Agency, 2004a; Environment Agency, 2004b). Flow will only occur between aquifer layers where there is a permeable connection, such as a fissure network (Environment Agency, 2004a; Environment Agency, 2004b). No information on flows between the Fell Sandstone Formation and surrounding aquifers has been seen in the literature consulted.

Groundwater flow systems in basement rocks over the structural highs and at depth across the region are typically very poorly understood. Extensive investigations of the hydrogeology of west Cumbria in the 1990s has provided an unusual level of insight into groundwater flow in the Borrowdale Volcanic Group, overlying Permo-Triassic Sherwood Sandstone Group and related rocks, and the East Irish Sea basin in the Sellafield area. Conceptual models indicate that groundwater recharging to the Borrowdale Volcanic Group flows first westwards and downwards, driven by gravity, with increasing salinity due to mixing with brines of the Irish Sea basin to the west, and then flows upwards because further westward flow is prevented by denser brines of the Irish Sea basin. Upward flow into the overlying Sherwood Sandstone Group aquifer appears to be restricted by low-conductivity geological units such as the St Bees Shale and St Bees Evaporite formations (Black and Brightman, 1996). Numerical modelling supports this conceptual flow model (Heathcote et al., 1996) suggesting that groundwater flowing from around 650 m depth could reach the surface in 15 000 years (McKeown et al., 1999). Recently, Black and Barker (2016) has modelled a region of observed high heads within the Borrowdale Volcanic Group beneath the coastal plain of west Cumbria and infers that the heads are a relic of recharge from a late Devensian ice sheet. Heads increase in with depth in the Borrowdale Volcanic Group and peak at a depth of about 1100 m before declining again. Such a model requires the Borrowdale Volcanic Group to have a low hydraulic diffusivity of the order of 10^{-6} m s^{-1}.

Based on the above observations, the overall hydrostratigraphy of the region is conceptualised as consisting of three broad groundwater systems:

- a groundwater system in west of the region comprising Permian to Triassic sediments, containing the Appleby Group (Permian) and Sherwood Sandstone Group (Triassic) principal aquifers, and in three distinct subregions:
    - west Cumbria
    - the Carlisle basin
    - Vale of Eden (associated with the Carlisle basin)
- a groundwater system in the north and east of the region within rocks of Carboniferous to Permian age, containing the Fell Sandstone Formation and the Zechstein Group (Magnesian Limestone) and underlying Yellow Sands Formation of early Permian age (Rotliegendes Group), all of which are classified as principal aquifers
- a relatively low-permeability system consisting of basement rocks and igneous intrusions of Ordovician to Devonian age

There are a range of pathways for groundwater movement between these groundwater systems, principally associated with regional-scale structures and with anthropogenic features (e.g. boreholes and mines). These potential pathways for groundwater movement between units and evidence for separation between groundwater systems are discussed after a description of each of the three groundwater systems.

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

6.3.1 Hydrogeology of the younger cover sequence

6.3.1.1 LIAS GROUP

Lias Group sedimentary rocks comprise mainly micaceous mudstone, interbedded with thin, calcareous siltstones and intermittent beds of fine-grained, micaceous sandstone (see Section 5). They may act to provide local supplies of groundwater, including from the Blue Lias Formation and the lower Lias Group, elsewhere in the UK (Jones et al., 2000) but in this region no hydrogeological data for unit has been seen in the literature sources consulted.

6.3.1.2 PENARTH AND MERCIA MUDSTONE GROUPS

The Mercia Mudstone Group and the overlying, thinner Penarth Group both occur at outcrop onshore in the Solway plain west of Carlisle (Figure 16). The Mercia Mudstone Group comprises mainly mudstone, locally with significant thicknesses of halite, and minor dolostone, dolomitic mudstone, nodular gypsum-anhydrite, common gypsum veins and thin beds of fine-grained sandstone (see Section 5). The Penarth Group comprises largely mudstones with siltstone laminae and thin sandstone interbeds (see Section 5). There is no hydrogeological information on these units in the region in the literature reviewed, however, the following generic observations can be made about the Mercia Mudstone Group.

Hydrogeologically, the group is generally considered to be a non-aquifer, particularly the mudstones within it (Jones et al., 2000). However, some parts of the group do yield limited quantities of groundwater where they are present at outcrop and shallow (< 200 m) depths: (Jones et al., 2000). Jones et al. (2000) describes how boreholes in the Mercia Mudstone Group in this region, as well as in other parts of England, often encounter saline or brackish water due to the common presence of halite deposits (as beds or cement) within the mudstones. Cooper (2007) describes the presence of known salt (brine) springs in Triassic strata in north-west England in this region, which emanated from actively dissolving halite karst in halite beds, and boreholes that intersected near-surface brine runs (flowing brine or mineralised groundwater), which helped exacerbate halite karstification. All these examples require that groundwater moves through the halites.

6.3.1.3 SHERWOOD SANDSTONE GROUP

The Sherwood Sandstone Group is the most productive principal aquifer in the region, widely used for water supply (Allen et al., 1997). It occurs in three basins in the west of the region: the Vale of Eden, Carlisle, and west Cumbria, including Furness, areas (Figure 16). It is immediately underlain by low-permeability Permian shales and evaporites, specifically the St Bees Shale, St Bees Evaporite and Eden Shale formations, and, where overlain by the Mercia Mudstone Formation, can be locally confined. The lowest part of the group is the St Bees Sandstone Member of the Chester Formation which comprises mainly fluviatile sandstones. The upper part of the group includes the former 'Calder Sandstone Formation' (assigned to the Wilmslow (formerly Calder) Sandstone Formation by Ambrose et al., 2014), and the former 'Ormskirk Sandstone Formation' on the Cumbrian coast and the former 'Kirklinton Sandstone Formation' in the Carlisle basin, both assigned to the Helsby Sandstone Formation by Ambrose et al. (2014), which all comprise mainly aeolian dune sandstones.

Matrix permeability is generally lower than bulk or field permeability, indicating that fractures largely control the rate of groundwater flow through the aquifer, at least at scales sampled by pumping tests (e.g. hundreds of metres) (Allen et al., 1997; 1998). However, at a regional scale (>1 km), fractures are considered to be less well connected, and matrix flow through poorly cemented, coarse-grained, well-sorted sandstone horizons with high intergranular permeability is thought to dominate groundwater flow (Allen et al., 1997; 1998). Matrix permeability values have been reported to cover five orders of magnitude from 9.8×10^{-16} to $9.8 \times 10^{-12} m^2$ (Bricker et al., 2012) reflecting the bed-scale heterogeneity of the Sherwood Sandstone Group (Bricker et al., 2012). Work at Sellafield concluded that bedding-plane fractures are possibly the most important contributor to borehole flow at depths of up to 200 m (Allen et al., 1998). Modelling of Environment Agency test data suggested that the bedding-plane fractures may have horizontal dimensions of the order of a few hundred metres (Allen et al., 1998). Dissolution of carbonate vein infills may be important to groundwater flow at these shallow depths (Allen et al., 1998).

Matrix and fracture permeability in the Sherwood Sandstone Group both decrease with depth. For example, constant-rate test pumping in a borehole at Sellafield at two intervals in the Sherwood Sandstone Group (141–296 m OD and 296–345 m OD) gave lower permeability values than were obtained from near-surface test pumping tests in other boreholes in the St Bees Sandstone Member (Allen et al., 1998). From such observations, Allen et al. (1997) states that the effective thickness of the St Bees Sandstone Member aquifer is likely to be around 100 m, because at greater depths the fractures are increasingly closed and the lithology becomes more fine grained and argillaceous. At depths greater than approximately 200 m, fractures are more likely to be steeply inclined and associated with faults (Allen et al., 1998).

Faults may be locally hydrogeologically significant in the aquifer. Some of the fault displacements are large enough for the Sherwood Sandstone Group to be juxtaposed against the Borrowdale Volcanic Group, causing potential hydraulic connection between the two units (Allen et al., 1998). Boreholes abstracting from the St Bees Sandstone Member that intersect fault zones have higher yields than those not intersecting fault zones (Allen et al., 1997). Faulting and associated fracturing in the Calder Valley in west Cumbria is thought to be associated with a high degree of hydraulic connection between the St Bees Sandstone Member (where it crops out inland) and the river (Allen et al., 1998).

Saline intrusion to the aquifer occurs in areas of heavy pumping on the Cumbrian coast, such as near Barrow-in-Furness (Stone et al., 2010). Where the aquifer is confined below the Mercia Mudstone Group, groundwater tends to be harder, with higher total dissolved solids and sulphate concentrations (Stone et al., 2010). In the Carlisle and Vale of Eden basins, high chloride, calcium and sulphate concentrations seen occasionally in groundwater in the Sherwood Sandstone Group, particularly at a site in the north-east of the Carlisle basin, have been linked to dissolution of gypsum and halite from evaporite-rich layers in the Mercia

Mudstone Group (former ‘Stanwix Shales’) (Daily et al., 2006a). Allen et al. (1997) states that the upper 200 m (approximately) of the group in west Cumbria form the effective freshwater aquifer, with a saline interface existing at a depth of about 300 to 700 m, generally at a boundary between geological formations or within the St Bees Sandstone Member or the Brockram Formation.

6.3.1.4 ZECHSTEIN AND ROTLIEGENDES GROUPS

The Permian Zechstein Group has highly variable lithology both laterally and vertically, but overall consists of several major sedimentary cycles, each with clastic rocks or dolomitic limestone at the base (the latter formerly known as the ‘Magnesian Limestone’ aquifer). These pass up into a varied suite of evaporite minerals that includes sulphate (e.g. anhydrite and gypsum) and chloride (e.g. halite). The unit is considered a principal aquifer by the Environment Agency, including the evaporites, as there is evidence that groundwater can move through these leaky aquitards, depending on the relative groundwater heads within the more permeable limestone layers and on the degree of dissolution and collapse of the evaporites. Consequently, the principal aquifer includes the Fordon Evaporite Formation, which has been identified as a PRTI (Table 3). ‘Magnesian Limestone’ is the now-obsolete name for the largely dolomitic limestones within the Permian Zechstein Group (Table 4). The terms ‘Magnesian Limestone’, ‘Lower Magnesian Limestone’, ‘Middle Magnesian Limestone’ and ‘Upper Magnesian Limestone’ are widely used in the hydrogeological source material referenced here, and are used in this section.

Table 4 Current and obsolete names for the limestones and dolomitic limestone aquifers within the Permian Zechstein and Rotliegendes groups

Group	Stratigraphical term (Durham)	Stratigraphical term (Yorkshire)	Hydrogeological term
Zechstein Group	Seaham Formation Roker Formation	Brotherton Formation	Upper Magnesian Limestone
	Ford Formation		Middle Magnesian Limestone
	Raisby Formation	Cadeby Formation	Lower Magnesian Limestone
Rotliegendes Group	Yellow Sands Formation	Yellow Sands Formation	Yellow Sands Formation

The Zechstein Group dolomitic limestone formations are used as an aquifer for public water supply in Durham and parts of Yorkshire. However, throughout the Zechstein Group, the dolomitic limestone aquifer units are interbedded with relatively low-permeability evaporite units. The formations in the Durham area are dominated by dolomitic limestones. The Lower and Middle Magnesian limestones are locally separated from the Upper Magnesian Limestone by marls (dolomitic mudstones), siltstones and evaporites (Allen et al., 1997). The aquifer units are underlain by the Marl Slate Formation, comprising organic-rich siltstones and dolomites, which in turn overlies weakly consolidated sand, sandstone and breccia representing aeolian dune deposits of the Yellow Sands Formation of the Rotliegendes Group, a principal aquifer (Stone et al., 2010; Allen et al., 1997). The Zechstein Group unconformably overlies Carboniferous rocks (Stone et al., 2010; Allen et al., 1997).

The Magnesian Limestone aquifer and the underlying Yellow Sands Formation exhibit good hydraulic connectivity, although they are locally separated by the Marl Slate Formation. Where the Marl Slate Formation is absent and where mining activities have created pathways, the Magnesian Limestone may also be in hydraulic connection with the underlying Pennine Coal Measures Group (Westphalian) (Environment Agency, 2016). Groundwater heads in the Pennine Coal Measures Group can be higher than in the Magnesian Limestone, producing an upward head gradient. Where this occurs, mine waters have to be managed by The Coal Authority to prevent upward movement of poor-quality groundwater from the Pennine Coal Measures Group (Environment Agency, 2016).

Where the Marl Slate Formation is absent, the Magnesian Limestone aquifer and the underlying Yellow Sands Formation are generally regarded as a single aquifer (Atkinson, 2004), with an observable lack of distinction in water chemistry between the two (Bearcock and Smedley, 2009). Atkinson (2004) states that, where the Yellow Sands Formation is present, it contributes considerably to resource availability, but the sands are thin, patchy and absent in areas. No aquifer properties data specifically for the Yellow Sands Formation were seen in any of the literature consulted for this report.

The hydrogeology of the limestone aquifer is largely controlled by lithology and structure, with the greatest control on aquifer properties being the extent of fracturing. As a result, aquifer properties are extremely unpredictable, with large ranges of permeability values (Allen et al., 1997). Permeability is dependent on fracturing and tends to be highest along major fault zones (Allen et al., 1997). Groundwater flow in the aquifer is predominantly along fracture systems, and two dominant fracture orientations, north-north-west and north-north-east, have been identified, which may influence groundwater flow directions (Atkinson, 2004). Numerous faults cut the limestones: in some cases they may act as partial barriers to flow, and in others they form high flow zones (Atkinson, 2004). Groundwater flow north of the West Hartlepool Fault is to the east, discharging to the sea, while south of the fault flow is towards the south-east towards the River Tees, which is a potential focus for groundwater discharge (Atkinson, 2004). Where the River Skerne flows over the aquifer there is thought to be quite a good connection between river and aquifer at specific points, with the river being a potentially significant recharge source for the aquifer (Atkinson, 2004).

The limestone aquifer in the Durham and Northumberland coalfield area is hydraulically connected to the underlying Carboniferous Pennine Coal Measures Group, as shown by the groundwater response in the aquifer during and following the cessation of mine dewatering in the Pennine Coal Measures Group. When coal mines were being dewatered, there was significant, vertical leakage from the limestone aquifer down into the mine workings (Atkinson, 2004). As water levels rebounded in the Pennine Coal Measures Group, they also rose in the overlying Magnesian Limestone; upward groundwater flow into the limestone aquifer from the Pennine Coal Measures Group is also shown by the migration of a highly mineralised groundwater plume through the limestone aquifer that originates from the Pennine Coal Measures Group (Bearcock and Smedley, 2009).

Allen et al. (1997) describes how collapse breccias are common in the Magnesian Limestone aquifer in Yorkshire, to the south of this region, due to the dissolution of gypsum in marls within the aquifer, which may be exacerbated by groundwater abstraction if greater water flow increases the rate of dissolution. This implies that groundwater must move through the gypsum. Cooper (2007) describes extensive karst features in gypsum in the Zechstein Group in Yorkshire, just to the south of this region, formed because the gypsum undergoes active dissolution as a result of groundwater flow.

Groundwater in the limestone aquifer in County Durham is mainly of Ca-Mg-HCO_3 type (Bearcock and Smedley, 2009; Atkinson, 2004). Groundwaters with high salinity have been found in coastal areas in the region, particularly around Hartlepool, associated with saline intrusion (Bearcock and Smedley, 2009; Atkinson, 2004). Relatively saline waters present in the area around the Durham and Northumberland coalfield are likely to result from minewater rebound following the cessation of mine dewatering in the 1970s (Bearcock and Smedley, 2009).

6.3.1.5 CUMBRIAN COAST GROUP

No hydrogeological data for the Cumbrian Coast Group and associated Permian rocks have been seen in the literature sources consulted.

6.3.1.6 APPLEBY GROUP — PERMIAN SANDSTONES

The Permian Appleby Group sandstone principal aquifer comprises the Penrith Sandstone, Brockram and Collyhurst Sandstone formations. The Appleby Group is present in the Carlisle and Vale of Eden basins, but only exploited significantly as an aquifer in the latter. It consists of aeolian dune sandstones, and the contemporaneous Brockram Formation comprises alluvial fan conglomerates and breccias (Allen et al., 1997). They are overlain by mudstones and associated evaporites of the St Bees Shale, Eden Shale and St Bees Evaporite formations.

Fractures largely control the rate of groundwater flow through the aquifer (Allen et al., 1997). However, groundwater flow in the Penrith Sandstone Formation is more intergranular in nature than in the St Bees Sandstone Formation, with high porosity and low hydraulic gradients (Allen et al., 1998). At a regional scale, the presence of poorly cemented, coarse-grained, well-sorted sandstone horizons with high intergranular permeability and porosity dominates groundwater flow, and the horizons with lower intergranular permeability in which fracture permeability dominates are of less significance (Allen et al., 1997). Bedding-plane fractures are a feature of the Penrith Sandstone Formation but there is little evidence that it becomes less permeable with depth as overburden causes fractures to close (Allen et al., 1998). Borehole yields increase with depth (Allen et al., 1997), however, this is thought to refer to the typical depths of water abstraction boreholes, which are approximately <200 m; there is relatively little information from greater depths.

Groundwater in the unconfined Penrith Sandstone Formation and near its outcrop is typically of calcium bicarbonate type. Groundwater confined beneath or close to the Eden Shale Formation can have higher total dissolved solids and sulphate concentrations as a result of groundwater flow from evaporites, and a monitoring borehole close to the Eden Shales Formation outcrop shows high sulphate concentrations, thought to be derived from the shales (Daily et al., 2006a).

6.3.2 Hydrogeology of the older cover rocks

The older sedimentary cover rock sequence includes the Warwickshire, Pennine Coal Measures, Millstone Grit, Yoredale, Border (Fell Sandstone) and Inverclyde groups and the Carboniferous Limestone Supergroup. It also includes the Carboniferous–Permian-aged Whin Sill igneous intrusion. Only the hydrogeology of the Whin Sill and the Warwickshire and Inverclyde groups (as PRTIs) and the Border (Fell Sandstone Formation) Group (principal aquifer) are described since the other units in this sequence are neither PRTIs nor principal aquifers, even though some of them may provide locally important supplies of groundwater.

6.3.2.1 Whin Sill and the Warwickshire Group

No hydrogeological data for either the Whin Sill or the Warwickshire Group in this region have been seen in the literature sources consulted.

6.3.2.2 Fell Sandstone Formation

The Carboniferous Fell Sandstone Formation crops out at the ground surface in the north and north-east of the region (Figure 16) and is part of the Border Group. It forms the most important principal aquifer within the Carboniferous sequence in Northern England (Jones et al., 2000), and is used for public water supply in the region, at Berwick-upon-Tweed, Wooler and Rothbury (Stone et al., 2010; Environment Agency, 2004a). The Fell Sandstone Formation is a sequence of sandstones and mudstones: at outcrop, it is typically a friable, medium-grained sandstone, with mudstones and intermittent, thin conglomerates (Jones et al., 2000). Surface pseudokarst features are associated with the formation (Jones et al., 2000).

The formation is hydrogeologically complex and multi-layered (Environment Agency, 2004a). It is most used for abstraction in the Berwick-upon-Tweed area. Pumping tests in the Murton Crags Sandstone Member indicated there was negligible leakage into the formation through underlying or overlying mudstones (Jones et al., 2000). Little is known about the aquifer to the south and west, but mudstone layers are thought to become more significant (Jones et al., 2000).

Matrix permeability is relatively low (Jones et al., 2000) and pumping tests have been interpreted to indicate that the majority of flow occurs in discrete horizons: fractures or thin, coarse-grained horizons (Jones et al., 2000). Observations during drilling have shown much groundwater associated with soft, sandy horizons at the base of sandstone units, which can show running sands (Jones et al., 2000). Vertical fractures with iron staining, indicating groundwater flow, have been noted in core samples as well as at outcrop (Jones et al., 2000). Particularly highly transmissive zones, marked by large springs, are associated with cross-cutting dykes intruded into fault zones (Jones et al., 2000). The deep Science Central Borehole in Newcastle upon Tyne proved more than 300 m of Fell Sandstone Formation from 1485 m downwards, with an elevated geothermal gradient of about 37˚C/km (Younger et al., 2015). Younger et al. (2015) infers that the Fell Sandstone Formation here may be hydraulically connected to the Weardale granite some 8 km away.

Regional groundwater flow in the Fell Sandstone Formation at less than 200 m depth in Northumberland is likely to be down dip towards the south-east, through fractures and fissures, but aquifer heterogeneities, particularly faulting and discontinuous aquifer layers, may lead to locally different flow patterns (Environment Agency, 2004a; Environment Agency, 2004b). Flow will only occur between aquifer layers where there is a permeable connection, such as a fissure network (Environment Agency, 2004a; Environment Agency, 2004b).

6.3.2.3 INVERCLYDE GROUP

The Inverclyde Group has a broad range of lithologies including sandstones, siltstones, conglomerates, mudstones, limestones, dolostones and locally anhydrite, as well as basalt lavas. Jones et al. (2000) presents no hydrogeological information specifically for the Inverclyde Group in England and Wales, but does briefly describe the hydrogeology of the early Carboniferous formations (formerly known as Dinantian aquifers (including the Carboniferous Limestone Supergroup)) other than the Fell Sandstone Formation. Limestones and sandstones within the aquifers are described as water bearing, while interbedded shales and mudstones act as aquicludes or aquitards (Jones et al., 2000).

The Inverclyde Group in north-east England consists of thin sandstone and limestone layers that act as separate aquifers, with intervening shales acting as aquitards, and groundwater storage and movement is predominantly in solution-enlarged joints and fractures. Groundwater flow is largely concentrated in larger conduits and directed towards discrete points of discharge, and groundwater flow directions are difficult to predict and may change markedly with variations in the water table (Environment Agency, 2004a).

There is no hydrogeological data for this unit in the region in the depth range of interest in the literature sources consulted.

6.3.3 Hydrogeology of the basement rocks

There is almost no information about the hydrogeological characteristics in the literature sources consulted for most of the basement rocks, however, there have been extensive prior hydrogeological investigations in the area of west Cumbria of the Borrowdale Volcanic Group. There is some information on the geothermal characteristics of the Ordovician granite plutons in the region.

6.3.3.1 CHEVIOT VOLCANIC FORMATION

The Cheviot Volcanic Formation comprises varied volcanic rocks originally formed as lavas, intercalated locally with sandstone. No hydrogeological data for this geological unit in the region have been seen in the literature sources consulted.

6.3.3.2 KENDAL GROUP AND RICCARTON GROUP

The Kendal Group of the Windermere Supergroup in south Cumbria consists predominately of mudstone and subordinate turbiditic siltstones, fine-grained sandstones and rare limestones, and the Riccarton Group in south-west of the Cheviot Hills consists of turbiditic sandstones interbedded with mudstones and siltstones.

Daily et al. (2006b) states that Silurian strata in the Lake District form a minor aquifer in which the effective aquifer is present only in the top few metres of weathered and fractured rock; that the hydrogeology is dominated by flow in these weathered and fractured near-surface regions, and that hydraulic conductivity values within unweathered strata of these rock types are typically very low, although few quantitative data are available.

6.3.3.3 DENT GROUP

The Dent Group of the Windermere Supergroup is mainly calcareous mudstone with limestone nodules, with subordinate calcareous sandstone, limestone, pyroclastic rocks, rhyolite lava and siltstone, with the uppermost Ashgill Formation comprising shales with lower calcareous content.

Daily et al. (2006b) states that Ordovician strata in the Lake District form a minor aquifer, in which the effective aquifer is present only in the top few metres of weathered and fractured rock; that the hydrogeology is dominated by flow in these weathered and fractured near-surface regions, and that hydraulic conductivity values within unweathered strata of these rock types are typically very low, although few quantitative data are available. Mineral springs rise from limestones in the Dent Group at Shap. Their chemistry suggests the slow circulation of peaty water along calcite-bearing mineral veins (Stone et al., 2010).

6.3.3.4 THRELKELD MICROGRANITE

The Threlkeld microgranite intrudes the lower part of the Borrowdale Volcanic and Skiddaw groups. No hydrogeological data for this geological unit in the region have been seen in the literature sources consulted.

6.3.3.5 Carrock Fell gabbro

The Carrock Fell gabbro is present in a narrow, steeply dipping zone in the Lake District, from the ground surface at outcrop and throughout the depth range of interest, and comprises layered gabbro intruded by dolerite sills. No hydrogeological data for this geological unit in the region have been seen in the literature sources consulted.

6.3.3.6 Borrowdale Volcanic Group

The Borrowdale Volcanic Group is found throughout the central part of the Lake District and is present within the depth range of interest throughout most of central Cumbria. It comprises basalt, andesite and dacite, and pyroclastic rocks, with associated intrusive igneous dykes and sills and many intercalations of volcaniclastic sedimentary rocks. There is much local hydrothermal alteration and mineral growth in the rock. Extensive hydrogeological investigations of the Borrowdale Volcanic Group in the Sellafield area were undertaken in the early 1990s. These are summarised in a series of papers in Heathcote et al. (1996).

Groundwater flow through the group occurs principally through fractures (Chaplow, 1996). Detailed testing of fracture flows in the group in boreholes showed that most of the fractures intersected by the boreholes had no detectable flow, and that fractures with flow are relatively widely spaced. Twenty flowing fractures were identified in 1140 m of volcanic rocks in one borehole; nine flowing fractures in 850 m in another, and eight flowing fractures in 770 m in a third borehole (Chaplow, 1996). Indications are that flow zones are not associated with any particular type or orientation of fractures (Chaplow, 1996). For some flow zones, pumping tests indicate that flowing fractures are hydrogeologically linked, possibly over hundreds of metres (Chaplow, 1996).

Bath et al. (1996) presents representative estimates of deep (about 650–1665 m depth) groundwater chemical compositions in the Borrowdale Volcanic Group beneath the Sellafield area. These indicate moderately saline groundwaters, increasing in salinity with depth. Bath et al. (1996) interprets this as the effects of mixing between modern recharge and very old (probably derived from pre-Pleistocene recharge) brines formed by partial dissolution of Permo-Triassic halites.

6.3.3.7 Skiddaw Group

The Skiddaw Group comprises mudstone, siltstone and sandstone. Daily et al. (2006b) states that Ordovician strata in the Lake District form a minor aquifer, in which the effective aquifer is present only in the top few metres of weathered and fractured rock; that the hydrogeology is dominated by flow in these weathered and fractured near-surface regions, and that hydraulic conductivity values within unweathered strata of these rock types are typically very low, although few quantitative data are available. Mineral springs flow from the Skiddaw Group near Derwent Water and Keswick. Their chemistry suggests the slow flow of groundwater along calcite-bearing mineral veins (Stone et al., 2010).

6.3.3.8 Lake District and north Pennines batholiths and the Cheviot pluton

In this region, this unit comprises the Lake District and north Pennines batholiths and the Cheviot pluton, all large intrusive bodies comprising granite with dolerite, dioritic and granodioritic rocks. Within the region, the north Pennines batholith only occurs buried at depth; the other two occur both buried and at outcrop. The available hydrogeological data for the Lake District and north Pennines batholiths are described. No hydrogeological data have been identified for the Cheviot pluton.

Lake District batholith

Heat flow investigation boreholes drilled to approximately 300 m depth into the Shap and Skiddaw granites showed values well above the UK average (corrected heat flow: Shap 77.8 mW/m^2; Skiddaw 100.9 mW/m^2) (Downing and Gray, 1986).

North Pennines batholith

A 995 m-deep exploration borehole at Eastgate, County Durham, penetrated 723.5 m of the Weardale granite (Manning et al., 2007). The borehole targeted the axis of a hydrothermal vein structure (the Slitt Vein). A single, large, open fracture in the granite in a depth interval of 410–431 m, on sustained testing over 24 hours, gave a transmissivity value in excess of 4000 darcy m (3 x 10^{-9}m^2/m), which is one of the highest values ever measured in a deep granite, and implies an average permeability of this zone of the order of 170 darcies (1.68 x 10^{-10} m^2) (Younger and Manning, 2010).

Other fractures were intercepted at depths from 436–814.5 m. Although individual or combined groundwater inflows from these fractures could not be discerned, gradually increasing groundwater temperature with depth in the borehole indicated that a significant amount of groundwater was flowing into the borehole below 410 m depth (Manning et al., 2007). Subsequent testing indicated that 99 per cent of the total transmissivity between 403 and 995 m depth is accounted for by the single fracture at 410–431 m depth (Younger and Manning, 2010). Testing of the borehole interval from 432–995 m depth gave a much lower transmissivity.

A heat-flow value for the Weardale granite of 95 mW/m^2 was calculated from the almost 400 m-deep Rookhope Borehole, with a geothermal gradient of about 31˚C/km (Downing and Gray, 1986); Manning et al., 2007 quote a similar geothermal gradient of 38˚C/km for the 995 m-deep Eastgate Borehole. There is some evidence that the Weardale granite is the source of warm and/or highly mineralised groundwaters; brines flow via major faults and/or mineral veins to younger rocks and/or to shallower depths (e.g. Manning and Strutt, 1990; Younger et al., 2015). Younger et al. (2015) refers to significantly high inflow rates to coal mines in Carboniferous rocks adjacent to the major Ninety Fathom Fault: 1.4 million l/d to the Rising Sun Pit, and 0.82 million l/d to the Eccles Pit. The inflowing groundwaters were unusually warm brines whose chemistry indicated equilibrium temperatures in the range of 150–200˚C, and are inferred to derive ultimately from the Weardale granite, transmitted through overlying and adjacent sedimentary strata (Younger et al., 2015).

A spring (sampled at 100 m OD in Weardale from the Slitt Vein in Cambokeels fluorite mine (Manning and Strutt, 1990) is thought to partly derive from the Weardale granite, the top of which lies about 80 m below the sampling site (Manning and Strutt, 1990). The part of the groundwater sample derived from the granite reflects geochemical reactions that appear to have taken place at temperatures of the order of 150˚C (Manning and Strutt, 1990), which are equivalent to a depth of 4 km (Manning and Strutt, 1990). There is no certainty about the full circulatory history or age of the groundwater discharging at the spring, with some evidence that it also reflects derivation from or reaction with Carboniferous sedimentary rocks (Manning and Strutt, 1990).

6.4 EVIDENCE FOR CONNECTIONS BETWEEN GROUNDWATER SYSTEMS

6.4.1 Geological pathways

6.4.1.1 THERMAL SPRINGS

No thermal springs (>15^{o}C) have been documented in the reviewed literature. Information on geothermal potential in the region is given in Section 8. The large granite intrusions in the region generate heat, and the region is consequently one of the geologically warmest regions of the UK. High geothermal gradients and heat-flow values for a number of granite bodies at depths of around 400–1000 m in the region have been observed.

There is some evidence that the Weardale granite at depth (possibly >1 km depth) is a source of warm and/or highly mineralised groundwaters that flow via major faults and/or mineral veins to younger rocks and shallower depths, including a spring discharge at the ground surface and underground coal mine workings (e.g. Manning and Strutt, 1990; Younger et al., 2015).

No other evidence for vertical groundwater flows from deep, warm rock units to shallower depths has been found in the literature consulted.

6.4.1.2 FAULTS

Faults can impact on hydrogeology in a number of ways, including by juxtaposing stratigraphically separated aquifer units and creating a hydraulic connection between them; acting as linear preferential conduits for groundwater flow, or acting as a barrier or restriction to groundwater flow.

Descriptions of the known effects of faulting are given in individual sections. Some particular examples are highlighted here.

- Some of the fault displacements in the Sellafield area are large enough for the Sherwood Sandstone Group to be juxtaposed against the Borrowdale Volcanic Group, causing potential hydraulic connection between the two units (Allen et al., 1998).

- There is some evidence that the Ninety Fathom Fault, part of an important fault zone in the region (Evans, 2016), together with an associated smaller fault, acts as a hydraulic connection between disconnected geological units, and as a conduit for unusually warm, highly mineralised groundwaters flowing ultimately from the Weardale granite via overlying and adjacent sedimentary strata and coal mine workings in Carboniferous rocks (Younger et al., 2015). Younger et al. (2015) also infers that the Ninety Fathom Fault connects the Weardale granite with the Fell Sandstone Formation at depths of greater than 1485 m.
- Igneous dykes intruded into fault zones in the Fell Sandstone Formation are associated with particularly highly transmissive zones, marked by large spring discharges (Jones et al., 2000).

6.4.1.3 ANTHROPOGENIC PATHWAYS

Information on mining and other anthropogenic resource development in the region is given in Section 8. Mine workings, both extant and collapsed, have the potential to form a pathway between deeper and shallower parts of the subsurface. There are several areas with clusters of deep (greater than 200 m below NGS datum) boreholes in the region, as shown in Figure 23. Deep boreholes are most likely to have been drilled in coalfield and mineral resource areas, or for deep geothermal energy exploration. Most of the mining-related deep boreholes are now likely to be disused. No evidence for vertical flows between rock units in deep boreholes has been found in the references consulted, but if the boreholes were not fully sealed when decommissioned, they could form pathways for vertical flows between permeable units, which would otherwise be hydraulically separated by intervening, low-permeability units.

There are a number of coalfields in the region, only two of which have been extensively mined: the Durham and Northumberland coalfield and parts of the west Cumbrian coalfield (see Section 8). Some of these were coastal mines, with workings extending up to 6 km offshore (see Section 8). At Whittle Colliery, about 7 km south of Alnwick, and at Ellington Colliery, about 10 km north-east of Morpeth, poor-quality water is pumped from disused mine workings at depth (the depths are not quoted in the source) (Environment Agency, 2004b).

7 Screening topic 4: natural processes

7.1 OVERVIEW OF APPROACH

Over the next one million years and beyond, a range of naturally occurring geological processes will continue to affect the landscape and subsurface of the UK. These processes have been active on and off throughout geological history and are likely to occur in the future. The range of processes and their impacts have been extensively reviewed by Shaw et al. (2012). However, only some of these natural processes are considered likely to affect the subsurface at the depth range of interest. These include glaciation, permafrost, seismicity and the effect of sea-level change on groundwater salinity (Shaw et al., 2012). Other naturally occurring geological processes that will occur over the next million years, such as surface erosion, surface weathering, tectonic uplift and subsidence, are not considered to be significant within the depth range of interest (Shaw et al., 2012).

This section provides an overview of the natural processes that may affect rocks to depths of between 200 and 1000 m in the Northern England region, specifically within a broader national context (RWM, 2016a). There is inevitably a high level of uncertainty relating to the future occurrence of the natural processes evaluated. This is especially true for future phases of glaciation and permafrost activity given the uncertainties surrounding climate change models. To overcome this, it is assumed that the climate change record of the recent geological past (one million years) provides a worst-case scenario of changes that may impact on the depth range of interest. It is not intended to be used, and should not be used, as an indicator of local-scale susceptibility as this may vary markedly across the region. Further assessment will be required to determine local-scale susceptibility.

This section is subdivided into three parts corresponding to glaciation, permafrost and seismicity. In each a national-scale context is provided, followed by a regional-scale evaluation for the Northern England region. Underpinning the national and regional evaluations of glaciation, permafrost and seismicity are a range of baseline data, information, scientific assumptions and workflows, which are described within the DTI (RWM, 2016b). Specifically, the DTI outlines the principal workflow that guides the expert through a set of key information and decision gateways, enabling evaluation and characterisation. A variety of generic assumptions and definitions are presented within the DTI and these underpin both the DTI workflow and the evaluation within the regional reports. Generic assumptions are based upon published geological information and include both scale-dependent and process-related assumptions. Data and information sources that underpin the workflow are listed. Principal data sources include Shaw et al. (2012), peer-reviewed publications and a digital elevation model, which is employed as a topographical base.

For glaciation, key terms are defined and the terminology employed to describe the extent and frequency of glaciation relative to known geological analogues is described. Several glaciation-related mechanisms are also described that may affect the depth range of interest. These include:

- glacial over-deepening
- tunnel valley formation
- isostatic rebound
- glacier forebulge development
- saline groundwater ingress in response to eustatic or isostatic change

7.2 GLACIATION

7.2.1 A UK-scale context

A glaciation or ice age is defined as a period of geological time when glaciers grow under much colder climatic conditions than the present day (Shaw et al., 2012; RWM, 2016b). A glacier is a body of ice that forms in the landscape and moves under its own weight (Shaw et al., 2012). Glaciers are typically initiated in highland areas where local and regional conditions enable the gradual build-up of snow, its progressive conversion to ice and subsequent flow (Shaw et al., 2012; Clark et al., 2004). With time, ice will form valley glaciers, which are constrained by large mountain valleys during periods of highland glaciations (Shaw et al., 2012). During prolonged cold periods and with the right local and regional conditions, glaciers may coalesce and expand into adjacent lowland areas forming a lowland glaciation (Shaw et al., 2012). Under extreme conditions and over thousands of years, lowland glaciers may, in turn, coalesce to form extensive ice sheets during a continental-scale glaciation (Shaw et al., 2012).

It is clear from the recent geological record that glaciers have been repeatedly active within the UK landscape over the past two and half million years (Clark et al., 2004; Lee et al., 2011). Numerous periods of glaciation have been recognised, although the scale and extent of glaciers have varied considerably. Most glaciations have been comparatively small (i.e. highland glaciations), although some have been more extensive with glaciers expanding into lowland parts of the UK, i.e. lowland glaciations (Clark et al., 2004; Lee et al., 2011). Over the past half a million years, at least two continental-scale glaciations have affected the UK with ice sheets covering parts of lowland UK, on one occasion as far south as the London area (Figure 17; RWM 2016b; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next million years is open to conjecture. This is because the impact of global warming and the current melting of the Greenland Ice Sheet on the long-term climate system are poorly understood although the general scientific view is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK, coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions, means that their occurrence cannot be discounted. Glaciers are important geological agents because they are highly effective at eroding and redistributing surface materials. Indeed, the landscape of much of Northern Ireland, Wales and northern and central England represents a legacy of past glaciation. Within the context of this report, glaciers can affect the subsurface within the depth range of interest by a variety of different mechanisms (RWM, 2016b).

- Glaciation can cause sea levels to vary relative to the position of the land either regionally, by natural cycles of sea-level change (eustatic change), or by localised loading of the Earth's crust by the mass of ice (isostatic loading); such glacier-induced sea-level change can cause or enhance saline water incursion into the shallow subsurface in coastal areas.
- Direct ice–substrate erosion or meltwater erosion at the base of the glacier can, over multiple episodes of glaciation, locally erode the subsurface to depths greater than 200 m.
- Uplift of the crust (glacier forebulge) in front of a glacier caused by loading may cause increased rock fracturing at depth, leading to some faults becoming reactivated and an increase in seismic activity.
- Isostatic unloading of the crust during and following deglaciation may cause increased rock fracturing at depth, leading to some faults becoming reactivated and an increase in seismic activity.

7.2.2 **A regional perspective**

Based upon geological evidence it is widely accepted that Northern England has been glaciated repeatedly during the past two and a half million years (Quaternary Period; Figure 17) (RWM, 2016b; Clark et al., 2004). The last known highland glaciation, which was restricted to some highland areas of northern England, ended just over 11 000 years ago during a time interval called the Younger Dryas. During the preceding glaciation, known as the late Devensian (about 29 000 to 15 000 years ago), several ice caps formed over highland areas of Northern England and coalesced to form a major sector of the last British–Irish ice sheet (Clark et al, 2004). This glaciation extended over much of northern and central UK and was the second of two known continental-scale glaciations to affect the UK (Loutre and Berger, 2000). Direct evidence for earlier glaciations in Northern England is preserved locally. However, the elevation of its highland source areas and the position of northern England relative to a prominent North Atlantic moisture source (the Gulf Stream) and other ice accumulations in Scotland made it highly susceptible to being glaciated (Clark et al., 2012).

Over the next million years, assuming Britain is glaciated, it is likely that Northern England will experience highland glaciation and potentially lowland and continental glaciation (Clark et al., 2012)). This is because the elevation of its highland source areas and proximity to other ice sources in Scotland and the prominent North Atlantic moisture source (the Gulf Stream) make it highly susceptible to glacier inception (Clark et al., 2012). During all scales of glaciation, glacial over-deepening of valleys in highland areas may, over multiple glacial cycles, cause the localised lowering of the ground surface into the very top of the depth range of interest, specifically in pre-existing valley areas (RWM 2016b). The formation of meltwater-incised valleys beneath glaciers (tunnel valleys) in lowland areas of Northern England adjacent to the margins of larger-scale lowland and continental glaciations may also result in the localised lowering of the ground surface into the very top of the depth range of interest (RWM 2016b). Collectively, over-deepening of glacial valleys and the formation of tunnel valleys can lead to the development of highly localised groundwater behaviour and chemistry (RWM 2016b). The region may also be affected by isostatic rebound and/or a glacier forebulge during a lowland or continental glaciation affecting an adjacent onshore and/or offshore region (e.g. Scotland, the North Sea or Irish Sea: RWM 2016b). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (RWM 2016b). The extensive coastline of Northern England makes coastal areas of the region susceptible to saline groundwater incursion due either to global sea-level change (driven by global patterns of glaciation) or regional isostasy (RWM 2016b). Saline groundwater incursion may alter the temporal and spatial patterns of groundwater behaviour (French, 2007).

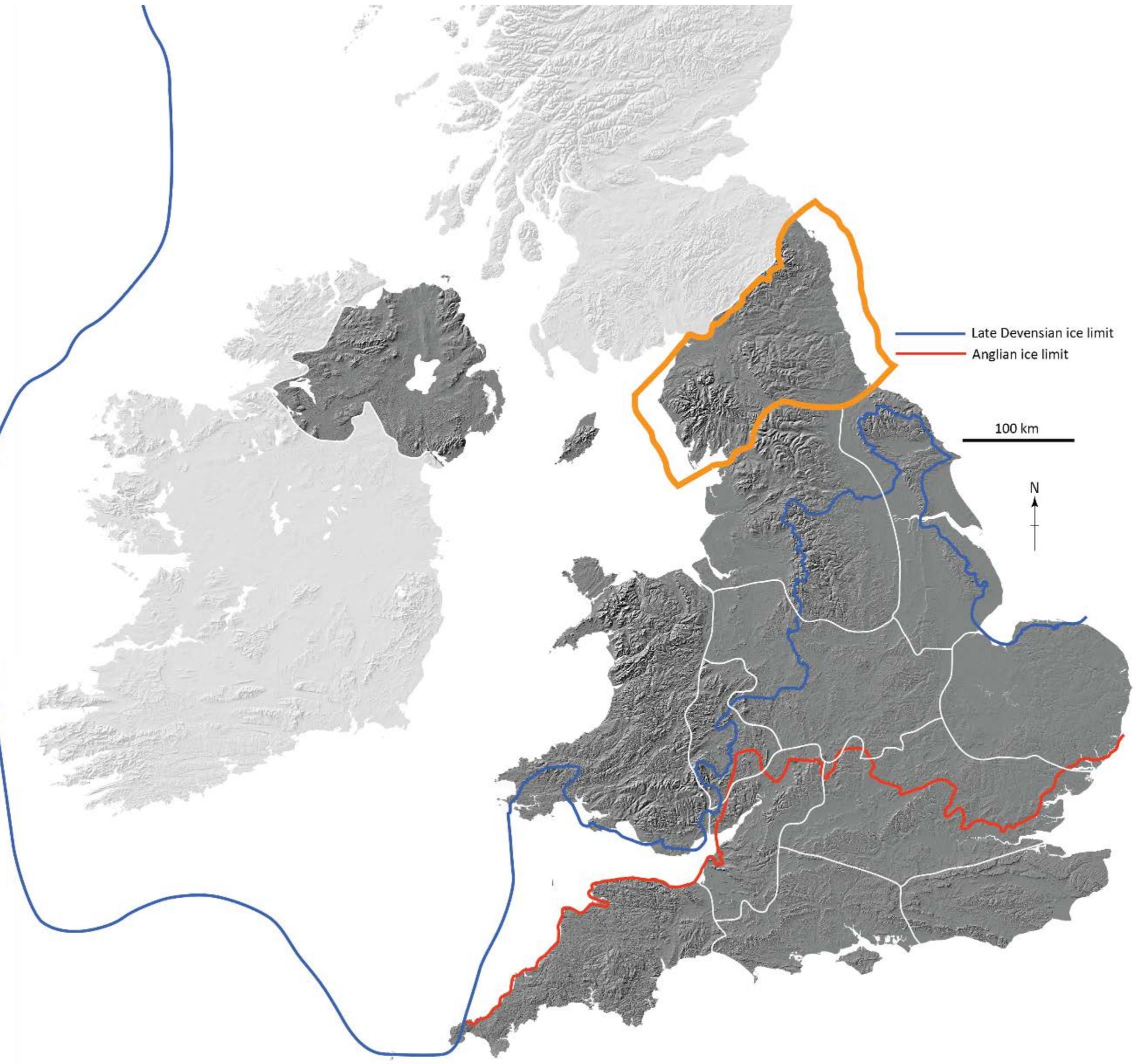

Figure 17 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and late Devensian (around 30 to16 ka). The location of the Northern England region is delineated by the orange line. Produced using Copernicus data and information funded by the European Union — EU-DEM layers ©EEA.

7.3 PERMAFROST

7.3.1 A UK-scale context

Permafrost (frozen ground) occurs when the temperature of the ground remains below 0°C for at least two consecutive years (French, 2007). Permafrost, therefore, develops where average air temperatures are much colder than the present day and consequently there is potential for significant thicknesses of permafrost to develop over decadal to centennial timescales (Busby et al., 2014). It is also important to note that permafrost and glaciation are not synonymous. Whilst many glaciated areas are subjected to periglacial processes, not all areas affected by permafrost will become glaciated. For example, areas situated to the south of the major limits of glaciation in the UK (see Figure 17) have all been affected by permafrost as indicated by the extensive weathering of surface geological materials (Shaw et al., 2012). Permafrost is important because its presence can affect the subsurface within the depth range of interest by altering groundwater behaviour and chemistry. This is especially the case if the current ground surface has been lowered by glacial erosion (Shaw et al., 2012).

Geological evidence demonstrates that all of the UK has been affected by the development of permafrost repeatedly over the past 2.5 million years (Busby et al., 2014). However, evidence for permafrost development is largely associated with the shallower parts of the permafrost profile (called the 'active layer') and evidence for the existence of deeper permafrost (i.e. permanently frozen ground) is lacking.

7.3.2 A regional perspective

Under future cold climates over the next million years, it is likely that Northern England will be subjected to the development of permafrost to a depth of a few hundred metres (Clark et al., 2004). The development of permafrost can affect groundwater chemistry and behaviour and, in combination with possible localised glacial erosion in highland areas, future development of permafrost may extend to several hundred metres beneath the current ground surface (RWM 2016b).

7.4 SEISMICITY

7.4.1 A UK-scale context

This section contains a description of the seismicity in the British Isles, including the wider regional context of the earthquake activity in Europe, the main features of the spatial variation of the seismicity in the British Isles and a statistical analysis of the UK earthquake catalogue. The study area is included in the rectangle between 49.9°N and 59°N latitude, and 8°W and 3°E longitude.

Earthquake activity is greatest at the boundaries between the Earth's tectonic plates, where the differential movement of the plates results in repeated accumulation and release of strain (Figure 18). However, earthquakes can also occur within the plates far from the plate boundaries, and where strain rates are low. Such earthquakes are commonly referred to as 'intraplate earthquakes'.

The UK lies on the north-west part of the Eurasian plate and at the north-east margin of the North Atlantic Ocean (Figure 18). The nearest plate boundary lies approximately 1500 km to the north-west where the formation of new oceanic crust at the Mid-Atlantic Ridge has resulted in a divergent plate boundary associated with significant earthquake activity. Around 2000 km south, the collision between Africa and Eurasia has resulted in a diffuse plate boundary with intense earthquake activity throughout Greece, Italy and, to a lesser extent, North Africa. This activity extends north through Italy and Greece and into the Alps. The deformation arising from the collision between the African and European plates results in compression that is generally in a north–south direction. The north-east margin of the North Atlantic Ocean is passive (i.e. transition between oceanic and continental crust) and is characterised by unusually low levels of seismic activity in comparison to other passive margins around the world (e.g. Stein et al., 1989). As a result of this geographical position, the UK is characterised by low levels of earthquake activity and correspondingly low seismic hazard.

The continental crust of the UK has a complex tectonic history formed over a long period of time. It has produced much lateral and vertical heterogeneity through multiple episodes of deformation, e.g. on the Highland Boundary Fault (Woodcock and Strachan, 2000), resulting in widespread faulting. Some of the principal fault structures represent major heterogeneities in the structure of the crust and have been the focus of later deformation. Earthquake activity in the UK is generally understood to result from the reactivation of these existing fault systems by present day deformation, although such faults need to be favourably orientated with respect to the present day deformation field in order to be reactivated (Baptie, 2010).

Focal mechanisms determined for earthquakes in the UK (Baptie, 2010) show mainly strike-slip faulting, with fault planes that are broadly subparallel to either a north–south or east–west direction. This is consistent with the dominant force driving seismicity here being first order plate motions, i.e. ridge push originating at the plate boundary in the mid Atlantic (Baptie, 2010). However, there is also evidence for isostatic adjustments having some effect on the principal stress directions expected from first order plate motions in Scotland (Baptie, 2010).

7.4.2 Seismicity catalogue

The earthquake catalogue considered in this assessment is based on the BGS UK earthquake database, which contains times, locations and magnitudes for earthquakes derived from both historical archives that contain references to felt earthquakes and from instrumental recordings of recent earthquakes.

The primary source of data for earthquakes before 1970 is the historical catalogue of Musson (1994), along with subsequent updates (e.g. Musson, 2004; 2007). It contains earthquakes of moment magnitude (Mw) of 4.5 and above that occurred between 1700 and 1970, and earthquakes of Mw 5.5 and above that occurred before 1700. Each event has a location and magnitude determined from the spatial variation of macroseismic intensity. This is a qualitative measure of the strength of shaking of an earthquake determined from the felt effects on people, objects and buildings (e.g. Musson, 1996).

The primary sources of data from 1970 to present are the annual bulletins of earthquake activity published by the BGS (e.g. Galloway et al., 2013). These contain locations and magnitudes determined from recordings of ground motion on a network of sensors in and around the UK (e.g. Baptie, 2012). The instrumental BGS database contains all events of Mw 3.0 and above, and some smaller earthquakes well recorded by the UK seismic network.

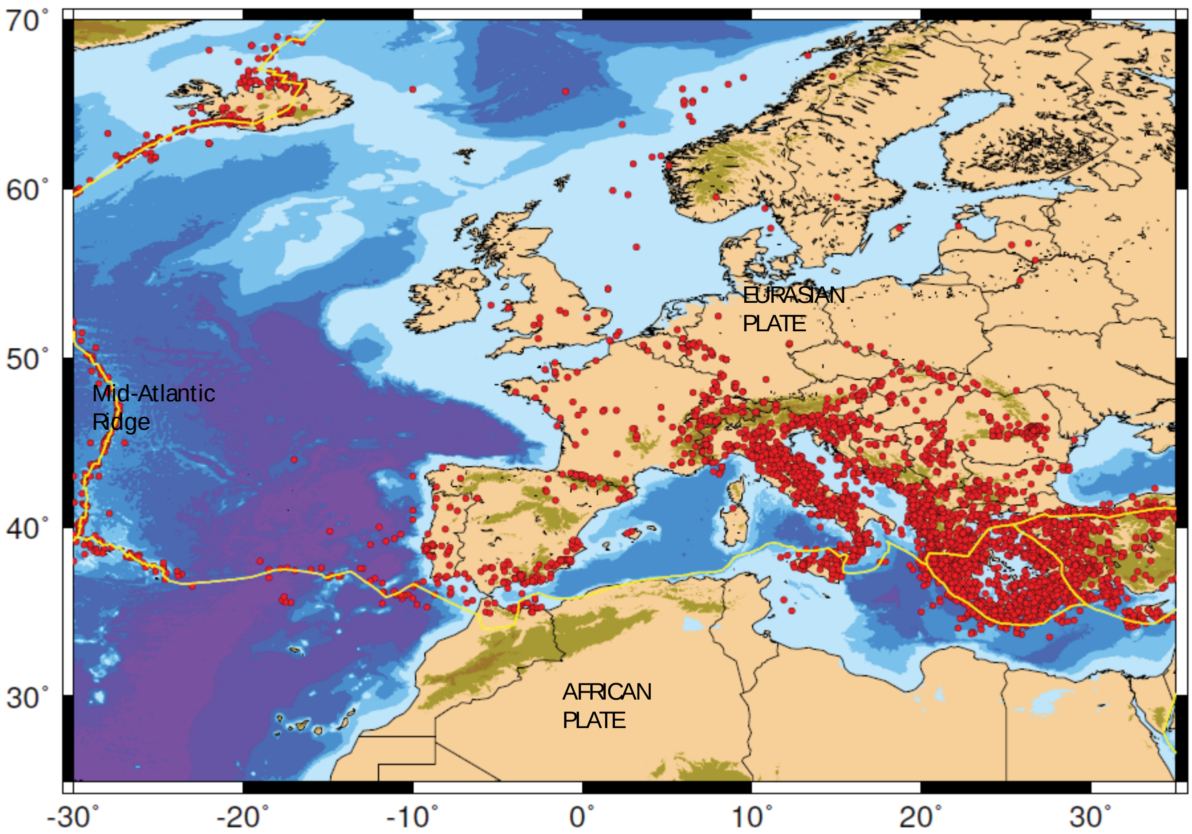

Figure 18 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

The BGS earthquake database is expressed in terms of local magnitude (ML). The ML was conceived for moderate earthquakes (magnitude between 2 and 6) recorded by a standard Wood-Anderson seismograph at distances between several tens and a few hundreds of kilometres (Deichmann, 2006). Therefore, it is inadequate to describe poorly recorded small earthquakes and larger earthquakes with limited numbers of on-scale records (Sargeant and Ottemöller, 2009). Since the beginning of the century, Mw has been recommended as a measure of earthquake size and is the preferred magnitude scale for ground motion models and seismic hazard assessment (Bolt and Abrahamson, 2003). Therefore for compatibility with the standard practice in seismic hazard assessment, the ML values have been converted to Mw, using the equation from Grünthal et al. (2009):

$$Mw = 0.53 + 0.646\ ML + 0.0376\ ML^2$$

This equation is based on a large dataset of earthquakes in Europe, including data from Fennoscandia.

For a statistical analysis of seismicity it is usually assumed that earthquakes have no memory, i.e. each earthquake occurs independently of any other earthquake (Reiter, 1990). This assumption requires removing the dependent events (i.e. fore and after shocks) from the earthquake catalogue to leave the mainshocks only. In the UK, the number of dependent events of significant magnitude (i.e. > Mw 3) is so small that it is easy and unambiguous to identify them by hand, which obviates the need to apply algorithmic methods.

The catalogue of main shocks for the British Isles covers a time window between 1382 and 31 December 2015. It contains 958 events of Mw 3 and above. The catalogue for earthquakes smaller than Mw 3 is not expected to be complete. Although events with Mw ≤ 3.0 are only significant for the possible light they might shed on seismogenic structures, it is necessary to take care, given that locations may have significant uncertainty.

A requirement for any statistical analysis of seismicity is that one needs to know the extent to which the record of main shocks in an earthquake catalogue is complete. For example, some historic earthquakes that happened may not be present in the catalogue because no record of them survives to the present day. Normally, completeness improves with time (better nearer the present day) and also with magnitude (better for larger earthquakes). Thus one can describe a series of time intervals within which it is considered that the catalogue definitely contains all earthquakes above a certain magnitude threshold. This threshold value can be defined as the lowest magnitude at which 100 per cent of the earthquakes in a space-time volume are detected (Rydelek and Sacks, 1989). Therefore it is usually low for recent seismicity and gets progressively higher back in time. For this study we use the completeness estimates for the UK catalogue determined by Musson and Sargeant (2007), which are shown in Table 5. The catalogue for earthquakes of Mw 3 and above is complete from 1970, i.e. the beginning of the instrumental monitoring of the British earthquakes. The catalogue is complete for earthquakes above Mw 4 and Mw 5 from 1750 and 1650, respectively. In south-east England, the catalogue extends further back in time (to the 14th century) for earthquakes of Mw 5.5 and above.

Table 5 Completeness values for the BGS seismicity catalogue (after Musson and Sargeant, 2007).

Mw	UK	South-east England
3.0	1970	1970
3.5	1850	1850
4.0	1750	1750
4.5	1700	1700
5.0	1650	1650
5.5	1650	1300
6.5	1000	1000

Figure 19 shows a map of all of the main shocks in the seismicity catalogue. The symbols are scaled by magnitude (Mw). It is worth noting that the location uncertainty is ±5 km for instrumental earthquakes and up to ±30 km for historical earthquakes (Musson, 1994). An analysis of the British seismicity clearly shows that it is not correlated with the major tectonic structures that bound the tectonic terranes in the UK (Musson, 2007). The terranes are homogeneous in terms of crustal properties (e.g. distribution and style of faulting), but the seismicity within each block is heterogeneous (Musson, 2007). There are spatial variations in the level of seismic activity across the UK. Western Scotland, western England, Wales, south-western Cornwall and the area off the coast of the south-eastern England are the areas of highest activity. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free (Figure 19).

It is generally observed that the geographical distribution of British seismicity of the modern instrumental period follows rather closely the same distribution as the historical record of the last 300 years. However, there are three significant exceptions to this: south-west Wales, the Dover Straits, and Inverness. In these areas there was an intense historical seismic activity (as shown by the squares in Figure 19), which does not correspond to an intense instrumental seismicity. The Dover Straits area is notable for having produced relatively major (≥5 Mw) earthquakes in historical times (the last in 1580) and very little since.

The largest earthquake in the catalogue is the 7 June 1931 Mw 5.9 event in the Dogger Bank area (Neilson et al., 1984). This is the largest UK earthquake for which a reliable magnitude can be estimated. The largest onshore instrumental earthquake in the UK is the 19 July 1984 Mw 5.1 event near Yr Eifel in the Lleyn Peninsula. Its hypocentre was relatively deep, with a focal depth of around 20 km (Turbitt et al., 1985). The event was followed by a prolonged number of after shocks including a Mw 4.0 event on 18 August 1984. There is evidence that earthquakes with magnitudes of Mw 5.0 or greater in this part of North Wales occur at regular intervals of about 150 years. For example, events similar to the 1984 earthquake occurred in 9 November 1854 (Mw 5.0), 7 October 1690, and probably July 1534 (Musson, 2007).

7.4.3 Earthquake depths

No earthquake in the UK recorded either historically or instrumentally is known to have produced a surface rupture. Typical fault dimensions for the largest recorded British earthquakes are of the order of 1 to 2 km. Therefore, it is difficult to accurately associate earthquakes with specific faults, particularly at depth, where the fault distributions and orientations are unclear and because of the uncertainties associated with depth estimates. The uncertainties in the focal depths determined for earthquakes are generally large, up to a standard deviation of ±10 km. Figure 20 shows the distribution of focal depths in the catalogue. These are distributed throughout the crust and the maximum depth in the catalogue is 28 km. This suggests that there is a relatively broad seismogenic zone, i.e. the range of depths in the lithosphere where earthquakes are generated. The larger earthquakes, e.g. the 7 June 1931 Mw 5.9 Dogger Bank earthquake and the 19 July 1984 Mw 5.1 Lleyn earthquake, tend to occur at greater depths.

Earthquakes with magnitudes of around Mw 5 nucleating at depths of 10 km or greater will not result in ruptures that get close to the surface, since the rupture dimensions are only a few kilometres. Similarly, smaller earthquakes would need to nucleate at depths of less than approximately 1 km to get close to the surface. An earthquake with a magnitude of Mw 6.0 or above, nucleating at a depth of less than 10 km and with an upward propagating rupture, could, in theory, be capable of producing a rupture that propagates close the surface. In this case, the expected average rupture displacement could be 20 cm or greater.

7.4.4 Maximum magnitude

The largest earthquake in the BGS earthquake catalogue has a magnitude of Mw 5.9 (i.e. the 7 June 1931 earthquake in the Dogger Bank area). However, in a low-seismicity region such as the British Isles, where recurrence intervals for large earthquakes are long (up to thousands of years), it is quite possible that the period of observations does not include the largest possible earthquake. This means that estimating the magnitude of the largest earthquake we might expect in the British Isles is difficult.

The maximum magnitude (Mmax) can be constrained by fault length, i.e. any large earthquake requires a sufficiently large structure to host it, and this certainly limits the locations where great earthquakes (M>8) can occur. In intraplate areas one cannot apply such criteria because there are many examples of strong (Mw 7) earthquakes occurring in virtually aseismic areas (e.g. Johnston et al., 1994). Furthermore, in any low-seismicity area, the length of the seismic cycle may be longer than the historical time window that captures the largest observed possible event (Musson and Sargeant, 2007). For these reasons, maximum magnitude is very much a matter of judgement in an area like the UK. Ambraseys and Jackson (1985) consider the largest possible earthquake in the UK to be smaller than Mw 6.0, considering the absence of any evidence for an earthquake above Mw 6.0 in the last 1000 years. For onshore seismicity the historical limit could be set even lower, around Mw 5.5 because historical onshore earthquakes have never been larger than Mw 5.1 (Musson, 2007; Musson and Sargeant, 2007). However, there is palaeoseismic evidence from Belgium for prehistoric earthquakes between 6.5 and 7.0 in magnitude (Camelbeeck and Megrahoui 1996;

Camelbeeck 1999). Therefore, we cannot rule out the occurrence of an earthquake that may have a larger magnitude than the largest magnitude observed in the British seismicity catalogue and may have occurred before the beginning of the historical catalogue.

The approach taken in the development of the seismic hazard maps for the UK by Musson and Sargeant (2007) is specifically intended not to be conservative: Mmax is defined as being between Mw 5.5 and 6.5 with Mw 6.0 considered the most likely value. In a seismic hazard assessment for the stable continental European regions including the UK, Giardini et al. (2013) considers maximum magnitude to be higher: between Mw 6.5 and 7.0 with a more likely value around 6.5.

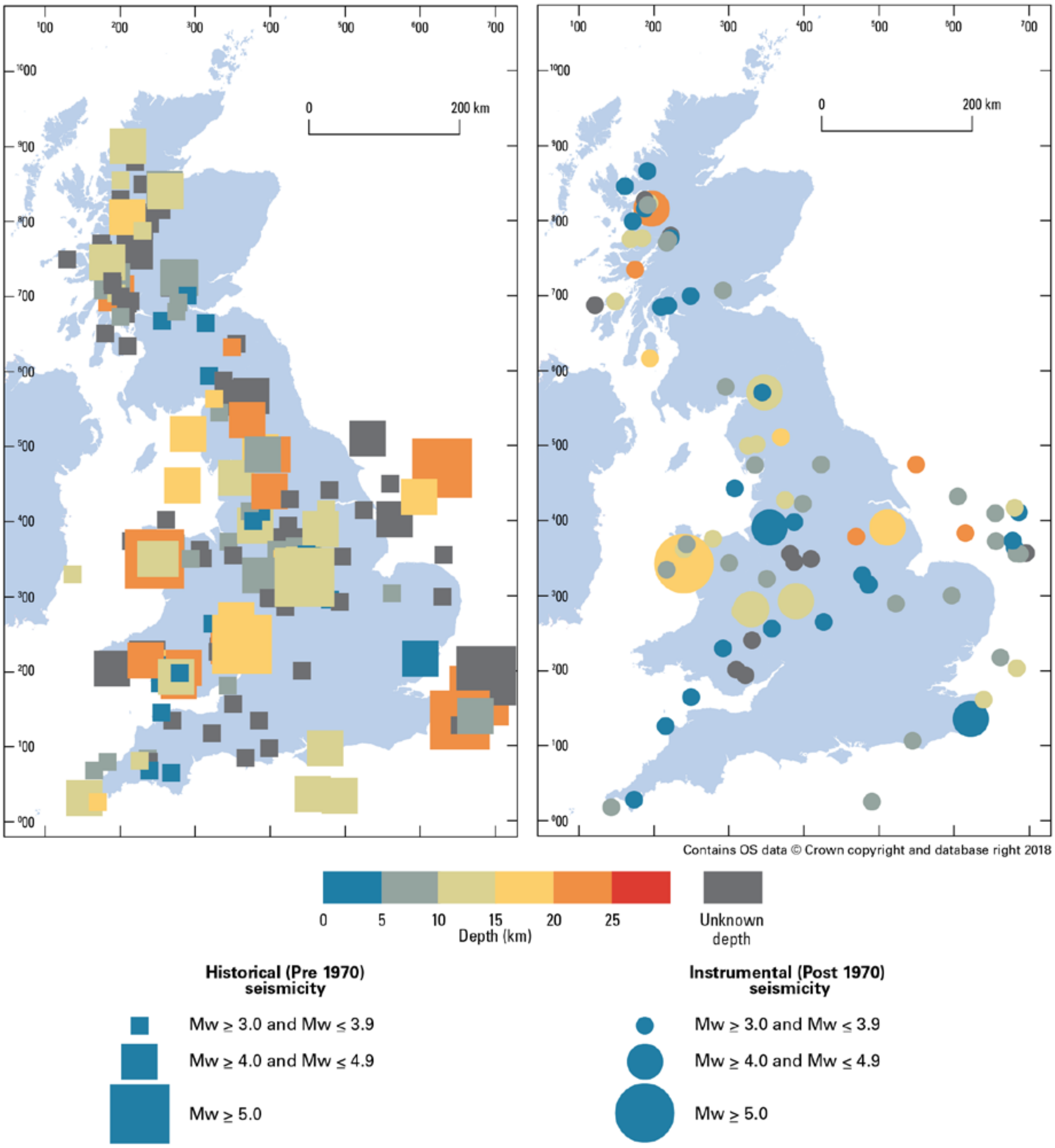

Figure 19 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

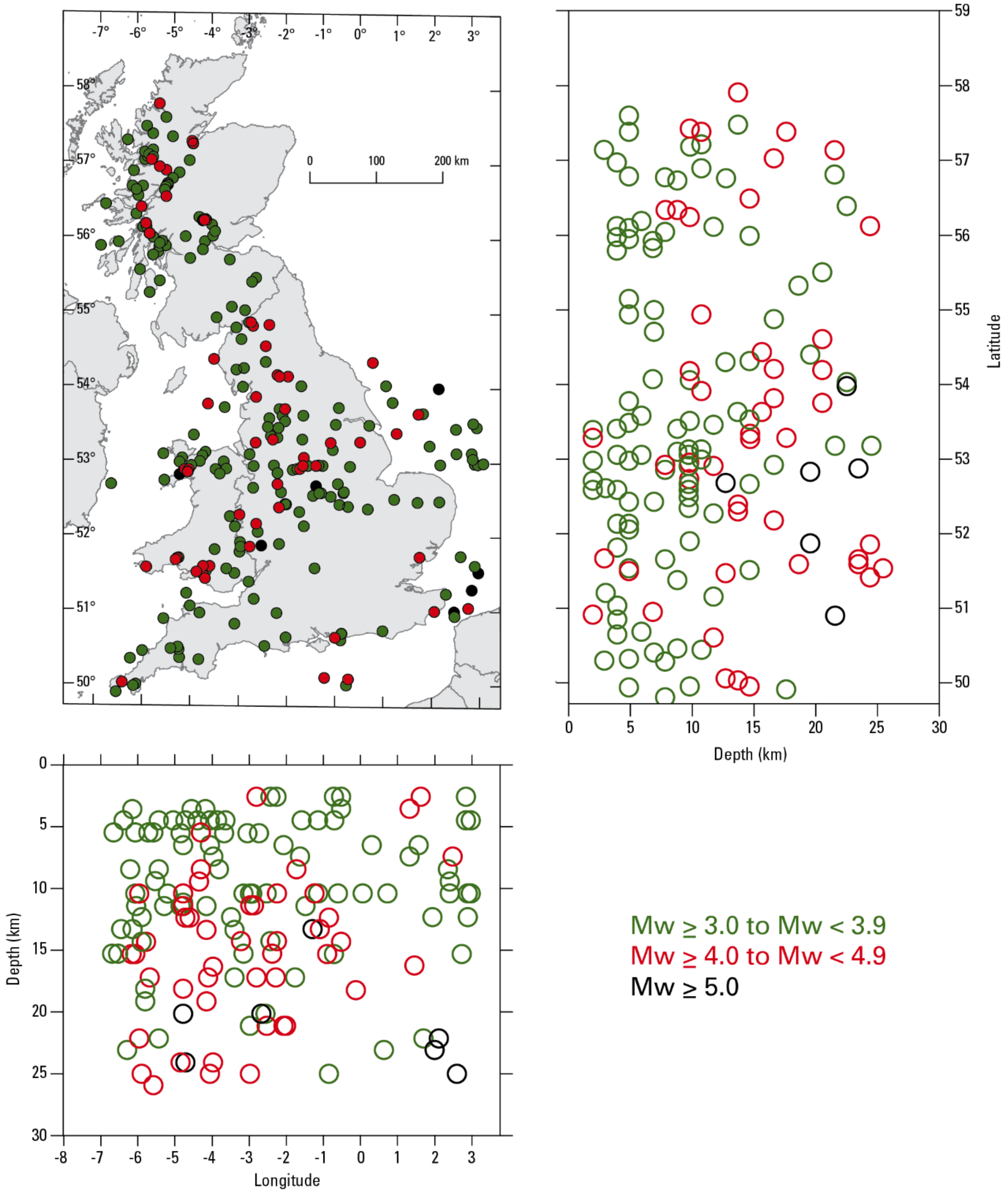

Figure 20 Relationship between the focal depth and the geographical distribution of the mains shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake-free. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

7.4.5 Earthquake activity rates

The relationship between the magnitude and number of earthquakes in a given region and time period generally takes an exponential form. This is referred to as the Gutenberg-Richter law (Gutenberg and Richter, 1954), and is commonly expressed as

$$\text{Log } N = a - b \text{ M}$$

where *N* is the number of earthquakes per year greater than magnitude M and *a* is the activity rate, a measure of the absolute levels of seismic activity. The *b*-value indicates the proportion of large events to small ones. Determining these parameters is not straightforward due to the limited time window of the earthquake catalogue and the trade-off between the two parameters. Furthermore, when the number of events is small, the uncertainty in the *b*-value is high. For this reason, it is desirable to be able to maximise the amount of data available for the analysis. The maximum likelihood procedure of Johnston et al. (1994) is one approach. This method is able to take into account the variation of catalogue completeness with time (Table 4) and computes a 5 x 5 matrix of possible values of *a* and *b* along with associated uncertainties while also taking into account the correlation between them.

We have used the method of Johnston et al. (1994) to calculate the *a* and *b* values for the UK catalogue described above and a polygon surrounding the British Isles. We find that the Gutenberg-Richter law is Log N = 3.266 to 0.993 M. This is roughly equivalent to an earthquake occurring somewhere in the British Isles with a magnitude of Mw 5 or above every 50 years. Both values are in keeping with the results obtained by Musson and Sargeant (2007) using only instrumental data. Extrapolating the derived relationship to larger magnitudes suggests an earthquake with a magnitude of Mw 6.0 or above may occur roughly every 500 years.

7.4.6 Impact of future glaciation

The possibility of renewed glaciation in the next ten thousand years means that estimates of the distribution and rates of regional seismicity cannot be considered the same as they are now. Geological investigations in a number of regions have found evidence for significant postglacial movement of large neotectonic fault systems, which were likely to have produced large earthquakes around the end-glacial period. For example, Lagerbäck (1979) suggests that the 150 km long, 13 m high fault scarp of the Pårve Fault in Sweden was caused by a series of postglacial earthquakes. Adams (1996) finds evidence for postglacial thrust faults in eastern Canada. Davenport et al. (1989) and Ringrose et al. (1991) find similar evidence for significant postglacial fault displacements in Scotland. However, Firth and Stewart (2000) argue that these are restricted to metre-scale vertical movements along pre-existing faults.

Some of the current understanding of the influence of glaciation on seismicity is summarised by Stewart et al. (2000). A number of studies (e.g. Pascal et al, 2010) suggest that earthquake activity beneath an ice sheet is likely to be suppressed and will be followed by much higher levels of activity after the ice has retreated. Consequently, estimates of seismicity based on current rates may be quite misleading as to the possible levels of activity that could occur in the more distant future. 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. Given our current maximum magnitude in the UK of around 6 it is not unreasonable to expect an increase in the maximum possible magnitude to 7 following such an event. However, it should be noted that postglacial fault stability is dependent on not only the thickness and extent of the ice sheet, but also on the initial state of stress and the properties of the Earth itself, such as stiffness, viscosity and density (Lund, 2005).

7.4.7 Conclusions

The level of seismicity in the UK is generally low compared to other parts of Europe. However, there are regions in the British Isles (e.g. Wales) that are more prone to the occurrence of future earthquakes than other areas. Furthermore, studies in the UK have estimated a maximum magnitude between 5.5 and 7.0 (Musson and Sargeant, 2007; Giardini et al., 2013). Although such an earthquake has a very low probability of occurrence, it may pose a potential hazard.

There are two crucial limitations in studies of British seismicity:

- The duration of the earthquake catalogue (approximately 700 years) is very short compared to the recurrence interval of large earthquakes in intraplate areas (thousands of years) and geological processes (millions of years). As a result, our understanding of earthquakes and earthquake generating processes is incomplete.
- The lack of surface ruptures does not allow us to associate seismic activity that has occurred with specific tectonic structures.

To estimate the likelihood of future earthquakes we use information from the past (historical and instrumental) seismicity via the earthquake catalogue. For these reasons, any conclusion on future seismicity in the UK is associated with large degrees of uncertainty.

7.4.8 A regional perspective

Figure 21 shows earthquake activity in the Northern England region. The western half of Northern England has experienced five earthquakes with magnitude of 4.0 Mw or greater in the last 500 years. The largest of these was a magnitude 4.7 Mw earthquake in 1786 just off the Cumberland coast near Whitehaven (Musson, 1994). Some minor damage was reported at Barrow, Cockermouth, Egremont, Whitehaven and Workington. A magnitude 4.7 Mw earthquake in 1871 had an epicentre between Appleby and Alston and was widely observed over the north of England, although little damage was reported. More recently, a magnitude 4.4 Mw earthquake near Carlisle in 1979 (King, 1980), close to the village of Longtown, caused some slight damage in parts of Carlisle. Damage included the fall of chimneys, slates and damage to plaster. The earthquake was felt widely in the north of England and Scotland and was followed by an aftershock sequence that lasted some months (Musson, 1994).

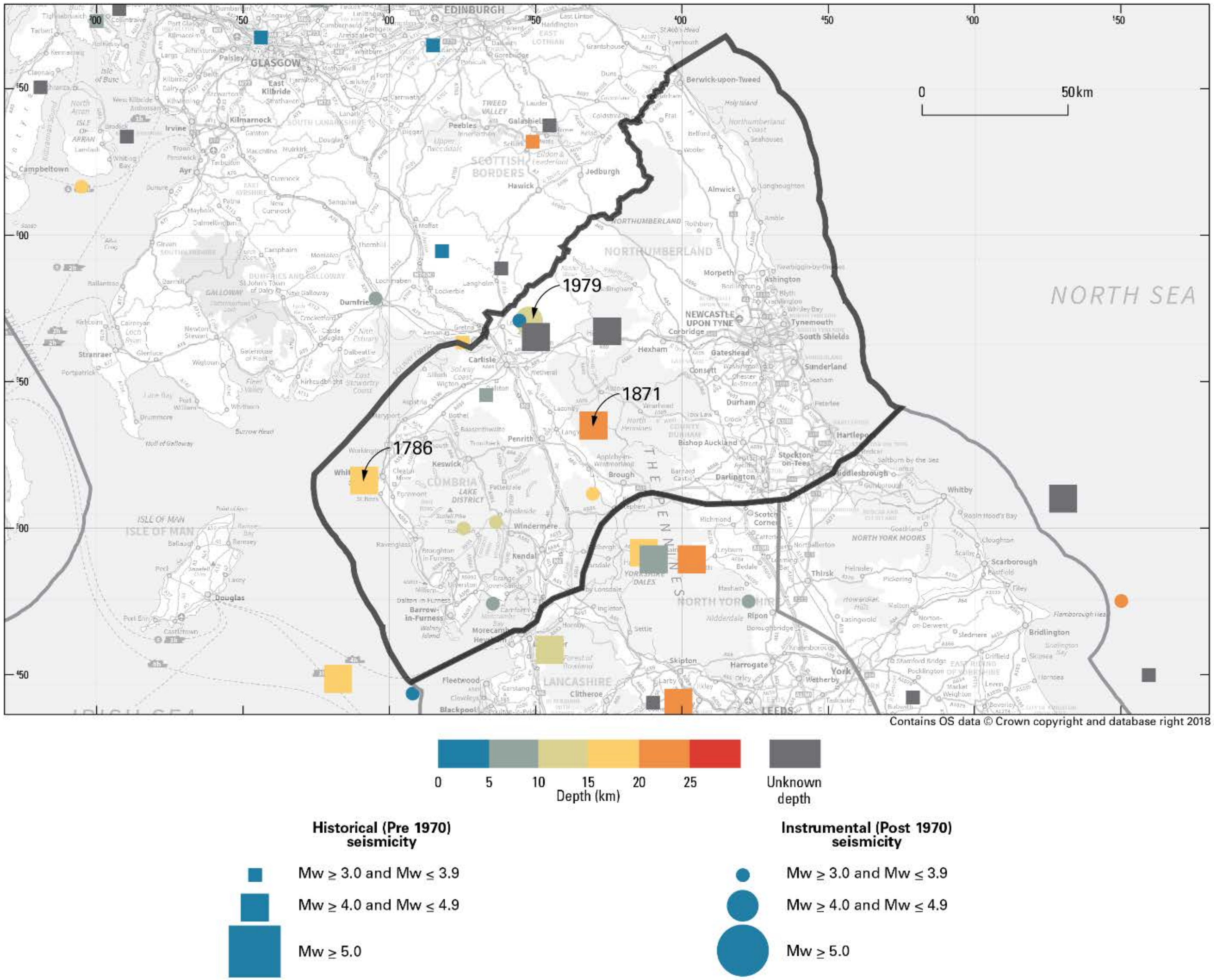

Figure 21 Historical and instrumentally recorded earthquakes in the Northern England region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

Mining has occurred, in some form, in Great Britain for over 4000 years. A diverse range of minerals has been extracted by underground mining, ranging from industrial minerals, such as limestone, through to precious metals like gold. Resources are primarily relevant to GDF safety because a future society, unaware of the presence and purpose of a GDF, may unwittingly drill or mine into the area in which the GDF is situated. Intrusion by people, including mining and drilling, may affect the geological environment and the function of the multi-barrier system. The voids and structures left after mineral exploration or exploitation may also provide a route by which deep groundwater may return to the surface environment.

This section explains what is known of mineral resources in the Northern England region. The extent of possible resources for groups of commodities is described, followed by the presence of any current workings or industrial infrastructure and their associated depths. The resources topic (Table 1) covers a wide range of commodities that are known to be present, or thought to be present, below NGS datum at depths greater than 100 m. These are grouped here into sections consisting of

- coal and related commodities
- potash, halite, gypsum and polyhalite deposits
- other bedded and miscellaneous commodities
- vein-type and related ore deposits

Geothermal energy, unconventional hydrocarbon resources and areas suitable for gas storage are also considered. Minerals worked in surface pits and quarries are not considered because such workings are considered to be too shallow to affect a GDF. A focus is given to resources that have been worked historically or are currently exploited, however, the presence of known but unworked resources is also discussed. This section also includes areas with a high density of deep boreholes and gives some detail as to the depth and purpose of boreholes in areas of where borehole density is highest in the region.

The resources DTI (RWM, 2016b) describes how the information on resources relevant to the NGS exercise has been prepared. Data for most commodities have been sourced from a wide range of already existing BGS datasets and the relevant data have been extracted and compiled here. For example the locations of coal resources are from the BGS 1:500 000 coal resource maps, evaporite mineral resources from the BGS county mineral resources maps, and hydrocarbon data from Oil and Gas Authority publications. No central dataset for metalliferous resources and mines exists, however, and for this a review of BGS memoirs, which list historic workings, was required. An important consideration in the assessment of all these resources was the depth at which they occur or at which they are worked. All recorded depths were therefore subject to the NGS datum correction to ensure areas of high topography were taken into account.

Also considered here are areas with a high density of deep boreholes. The locations of these have been sourced from the BGS Single Onshore Borehole Index database (SOBI) and represent areas where:

- there is more than one borehole, over 200 m deep, in a 1 km grid square that has one or more deep boreholes in an adjacent grid squares
- there are more than two deep boreholes in a given 1 km grid square.

The term ‘mineral resource’ can have several definitions. For the NGS, the definition in the guidance document was adhered to, which describes resources as ‘materials of value such as metal ores, industrial minerals, coal or oil that we know are present or think may be present deep underground’ (RWM, 2016a).

8.2 OVERVIEW OF RESOURCES IN THE REGION

The distribution of mineral resources in the Northern England region is shown in Figure 22. The Northern England region contains a number of coalfields, some of which have been extensively mined, in particular the Durham and Northumberland coalfield. There are no hydrocarbon fields in the region. There are several orefields, including the Alston block of the northern Pennine orefield, which has been extensively worked for lead, zinc and fluorite and the west and south Cumbrian iron orefields. The region has several gypsum and anhydrite mines. There are salt caverns for gas storage in the south-east of the region.

8.3 COAL AND RELATED COMMODITIES

There are several coalfields in the region. The largest is the Durham and Northumberland coalfield with extensions along the Northumberland coast and offshore beneath the North Sea. There are smaller coalfields in west and north Cumbria, the Vale of Eden and in the Alston area of the Pennines. The Durham and Northumberland coalfield and parts of the coalfield areas in west Cumbria have been extensively exploited but elsewhere the coal remains largely unexploited. There are no deep coal mines still working in the region, although small-scale, shallow mining continues in the Alston area.

The exposed Durham and Northumberland coalfield occupies a broad outcrop over 32 km in width extending eastward from Consett in the west towards the coast. East of a line through Ferryhill and Boldon and extending to the offshore area, the coalfield is concealed beneath younger rocks. With workings recorded as far back as 1188, the Durham and Northumberland coalfield was perhaps the first British coalfield to be developed commercially, and the first deep mine was sunk in 1820 at Hetton Colliery. Exhaustion of reserves and economic factors led progressively to the closure of all the mines towards the end of the 20th century, with large-scale deep mining ending in 1993 with the closure of the Vane Tempest Colliery. During the final years of deep mining, coal extraction became concentrated in a few amalgamated coastal collieries, in which workings extended up to 5 km offshore.

In Cumbria, the principal source of coal is the west Cumbrian coalfield. An isolated outcrop of Pennine Coal Measures Group rocks in the north-east of the region, around Midgeholme, has also yielded significant tonnages. The main west Cumbrian coalfield occupies a comparatively narrow, near-coastal outcrop that extends northwards from Whitehaven, through Workington to Maryport and thence eastwards to Aspatria and Bolton Low Houses. Further east, very poorly exposed Pennine Coal Measures Group rocks also occur in the Vale of Eden, though no coal of economic value has been recorded in this area. The west Cumbrian coalfield has enjoyed a long and distinguished history of coal production with records of mining known from at least the mid-16th century to the present day. It was, however, the latter half of the 19th and early part of the 20th centuries that witnessed the heyday of the industry. Abundant, high-quality coking and steam coals, together with the large local deposits of haematite iron ore, provided the foundation for the heavy industrial economy of west Cumbria.

During its peak years of production, almost the entire output of coal from the Cumbrian coalfield was obtained from underground mines. During the final years of deep mining, coal extraction became concentrated in a few coastal collieries in which workings extended up to 6 km offshore. Large-scale deep mining came to an end in 1984 with the closure of the Haig Colliery at Whitehaven.

In the Alston area, thin coal seams hosted in Namurian strata that are slightly older than the more productive Pennine Coal Measures Group are currently being worked intermittently at relatively shallow depths (up to about 100 m below NGS datum).

There are currently Coal Authority licences for underground coal gasification off both the east and west coastal areas of the region, around Whitehaven and Workington, the Solway Firth and along the east coast between Hartlepool and Alnwick. Very little exploration has been conducted in these areas. There is no current active exploitation of coal mine methane, abandoned mine methane or coalbed methane in any of the coalfield areas.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

Anhydrite has been mined in west Cumbria, near Whitehaven, and at Billingham and Middlesbrough in the south-east of the region. Gypsum has been extensively exploited in the Vale of Eden.

In the Vale of Eden, near Whitehaven in west Cumbria and in south Cumbria several gypsum/anhydrite beds occur within mudstones of late Permian age. Several beds have been worked for both gypsum and anhydrite, and formed the basis of a large mining industry in the past. Mining of anhydrite is now on a very much reduced scale, but the Vale of Eden remains one of the major centres of gypsum production in Britain. Mining is now confined to the Kirkby Thore, area where it is mined up to about 200 m below NGS datum. Mining has also taken place at the Longriggs, Newbiggin and Long Meg mines (which closed in 1973), although only the Long Meg Mine extends to over 100 m below NGS datum.

Two evaporite mines, Barrowmouth and Sandwith, worked gypsum/anhydrite up to a depth of around 200 m below NGS datum on the west Cumbrian coast. Gypsum was worked underground at the Barrowmouth Mine at Saltom Bay, south of Whitehaven, but increasing proportions of anhydrite in the bed led to the mine’s closure in 1908. Anhydrite was mined on a large scale at the Sandwith Mine beneath St Bees Head and offshore for use locally in the manufacture of sulphuric acid and by the cement industry as an additive. The mine started production in 1955 and produced some 8 million tonnes of anhydrite prior to its closure in 1975.

Small amounts of salt from brine have also been extracted around Walney Island, Barrow-in-Furness, but extraction has now ceased. The Walney Island salt deposits are continuous with the more extensive deposits offshore in the East Irish Sea, together with those formerly worked at Preesall in west Lancashire. They are highly unlikely to be of economic interest in the future, either as a source of salt or for the development of storage cavities, because of the presence of wet rockhead and the fact that individual halite beds are thin.

Evaporite deposits around Middlesbrough, Darlington and Hartlepool are of considerable economic importance. The Billingham Anhydrite Formation was extensively mined on Teesside between 1927 and 1971 as a source of sulphur for the manufacture of ammonium sulphate fertiliser and sulphuric acid. The Billingham anhydrite mine was sunk to a depth of 270 m below NGS datum in 1926 to intercept the formation, mining being at an average depth of about 220 m. The mine closed in 1971 because of a decline in demand. Approval was granted in 2011to use part of the old mine workings for toxic waste disposal.

One of the thickest evaporite units, the Boulby Halite Formation, has formed the basis of the Teesside chemical industry. Salt has been worked here until recently by brine pumping for feedstock for the chemical works, and much of the area east of Billingham has been subjected to brine pumping.

8.5 OTHER BEDDED AND MISCELLANEOUS COMMODITIES

There are no deposits of bedded or other miscellaneous deposits that have been worked deeper than 100 m below NGS datum in the region, however, a number of commodities have been mined at shallower depths in the region including building stones and slate.

8.6 VEIN-TYPE AND RELATED ORE DEPOSITS

Areas that have undergone deep mining for vein-type ore deposits have been identified from the location of deep mine shafts and the known location of mineral veins. In most cases mine plans are not available or not accurate enough to delineate the surface expression of underground workings.

Iron ores have been mined from depths greater than 100 m below NGS datum in west and south Cumbria. Parts of the Lake District form a copper, lead and zinc orefield and include three mines that have been worked to depths greater than 100 m below NGS datum. The Greenside Mine (which closed in the early 1960s) worked to about 165 m below NGS datum.

The Alston–Weardale area forms the Alston block of the northern Pennine orefield. This consists of the main orefield and the Settlingstones area, and has been worked extensively for lead for many centuries. More recently, it has been worked for zinc and into the early 1990s for fluorite. In total, 14 of the mines exceed 100 m below NGS datum, although the majority of the mine workings do not exceed this depth. The deepest mines such as Whiteheaps and Settlingstones exceed 200 m depth below NGS datum.

There are a few mines that have been worked to depths greater than 100 m below NGS datum outside the main orefield areas and these are shown on Figure 22.

Some of the most extensive deep mineral workings for metallic minerals in this region are for iron ore in west Cumbria. Large deposits of iron ore were worked to a maximum depth of almost 300 m below NGS datum in the area between Lamplugh and Calder Bridge in the west Cumbrian orefield. Iron ore was also extracted in the Millom and Furness areas of the south Cumbrian orefield, where mines reached a maximum of 190 m below NGS datum. The earliest records of haematite mining in Cumbria date from the 12th century and mining is known to have been active in the 17th and 18th centuries. Large-scale exploration and mining during the 19th century culminated in the peak years for production. Throughout the first half of the 20th century, both the west and south Cumbrian orefields continued to supply substantial tonnages of ore to the steelworks at Barrow, Millom and Workington. Progressive exhaustion of the largest ore bodies, failure to locate large new reserves, changes in steel-making technology and a variety of economic difficulties brought about a severe decline in the fortunes of the Cumbrian iron ore mining and smelting industry in the second half of the 20th century. This led to the closure of the last south Cumbrian mine, Hodbarrow Mine at Millom, in 1968 and the closure of the combined Florence–Beckermet Mine at Egremont in 1980.

Although there has been extensive working of copper, lead, zinc and tungsten deposits in Cumbria, few mines worked 100 m below NGS datum. A cluster of copper mines around Coniston, Tilberthwaite and Greenburn reached a maximum depth of 280 m below NGS datum. Brandlehow, Goldscope and Greenside mines, working copper and lead, reached around 170 m below NGS datum. The last of these to close, in 1962, was Greenside Mine, one of the UK's largest lead mines, located in Glenridding.

More extensive deep working of vein minerals took place in the northern Pennine orefield, centred around Wearhead. The most important metal ores were lead and iron, with some by-product silver. Zinc ores have also been mined locally and their exploitation extended the working lives of many lead mines in the Nenthead and Alston areas. Total production of lead concentrates for the whole orefield has been estimated at some three million tonnes and peak metal-mining activity was achieved in the mid to late 19th century. Mining for metal ores as the principal product ended in the late 1930s. The mines continued to be worked for fluorspar, mainly at shallow depths, until more recently. Mine depths are typically between 100 and 200 m below NGS datum with the deepest being Whiteheaps at around 240 m below NGS datum. Mining is extensive in the Weardale area, however, most mines here do not exceed depths of 100 m below NGS datum.

The only deep mineral workings to the east of the northern Pennine orefield in this region are where barytes has been extracted from coal mines, for example from Morrison Pit in County Durham.

Recent exploration drilling undertaken in the Nenthead area has identified deep (500 m below NGS datum) resources of lead and zinc that may be exploited in future.

The orefields shown on Figure 22 delineate the areas where most of the known mineralisation is located, however, large parts of these areas are not intensively mineralised and have not been extensively mined or mined to depths exceeding 100 m below NGS datum. There are also known mineral veins that have been mined in the past outside the main orefield areas but most of these have not been extensively mined or mined to any significant depth. Because of the widespread distribution of mineral veins and the extent of past shallow mine workings in these areas, the mineral potential may be re-examined in the future.

8.7 HYDROCARBONS (OIL AND GAS)

There are no conventional hydrocarbon fields on or offshore in the region, although tracts offshore are currently covered by hydrocarbon exploration licences, as are small areas around Barrow-in-Furness and Hartlepool. None of the region has currently been identified as having any prospectivity for shale oil or gas.

8.8 GAS STORAGE

Underground gas storage (UGS) facilities are in operation in the region. Former brine caverns in the Teesside salt field have been converted and are used for storage purposes in the extreme south-eastern parts of the region, extending into the parts of the adjacent northern extent of the Eastern England region. The Teesside salt field comprises thin halite beds of the (Middle or Main) Boulby Halite Formation (Permian age, Z3 cycle). These form the Billingham, Saltholme, Greatham and Wilton brine fields, from which brine has been produced by solution mining for many decades. Products stored include various industrial wastes, gas, LPG and hydrogen. The caverns are in the general depth range 350–500 m below NGS datum, within the maximum depth of 1000 m being considered. Offshore, within the 20 km zone, these halite beds deepen eastwards but will generally also be at depths within the range being considered for gas storage use.

8.9 GEOTHERMAL ENERGY

The Northern England region is underlain by the Lake District batholith in the west and the north Pennine granitic batholith to the east (also known as the Weardale granite). These granite bodies are radiothermal, which means the decay of natural radioactive elements generates heat within the rock. Consequently, Northern England shows some of the highest geological heat flow in the UK.

Heat flow rates in the region are up to of 100 mW/m^2 coinciding with geothermal gradients of >35ºC per kilometre. This would mean temperatures of 150ºC would be encountered at depths of 4.5 km below NGS datum, and 200ºC at 6 km depth.

In 2004 a geothermal energy exploration borehole was drilled at Eastgate, Country Durham, to target a deep mineral vein, known as the Slitt Vein, within the north Pennine granitic batholith. The borehole was drilled to a depth of 925 m giving a bottom-hole temperature of 46ºC, with very high transmissivities (in excess of 4000 Dm). This result was confirmed by a second borehole in 2010. Geothermal energy plants that successfully intercept these permeable zones or artificially increase the permeability of the granite could supply heat to local communities.

Carboniferous sedimentary sequences provide targets across the whole region. In 2014, the Science Central Borehole was drilled in Newcastle upon Tyne to intercept permeable fractures in the Fell Sandstone Formation, with warm waters sourced from the nearby north Pennine batholith. The borehole recorded temperatures of 73ºC at 1700 m below NGS datum, indicating a geothermal gradient of 36ºC/km, however, the high-permeability zones targeted were not intercepted.

Locally there is the potential for minor district heating schemes using ground-sourced heat pumps in abandoned mine workings from the various coalfields across the region. An abandoned coal mine water-heating scheme is currently being exploited by the Coal Authority at Dawdon, County Durham, and producing 12KW of energy to heat local offices.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are several areas with clusters of deep (greater than 200 m below NGS datum) boreholes in the region, as shown in Figure 23. These are in two main areas: the Durham and Northumberland coalfield and its offshore extension in the east of the region, and in west Cumbria to the west. In the former area they have mainly been drilled for evaluation of the coal deposits of the eastern part of the Durham and Northumberland coalfield and the evaporite deposits in the Middlesbrough area (where densities can reach over 60 boreholes/km^2). Boreholes in the west of the region have been drilled mainly to evaluate coal deposits, iron ore resources and as part of the Nirex Sellafield investigations. The highest densities can be as much as 40–50 boreholes/km^2 around Egremont; these were drilled for iron ore exploration.

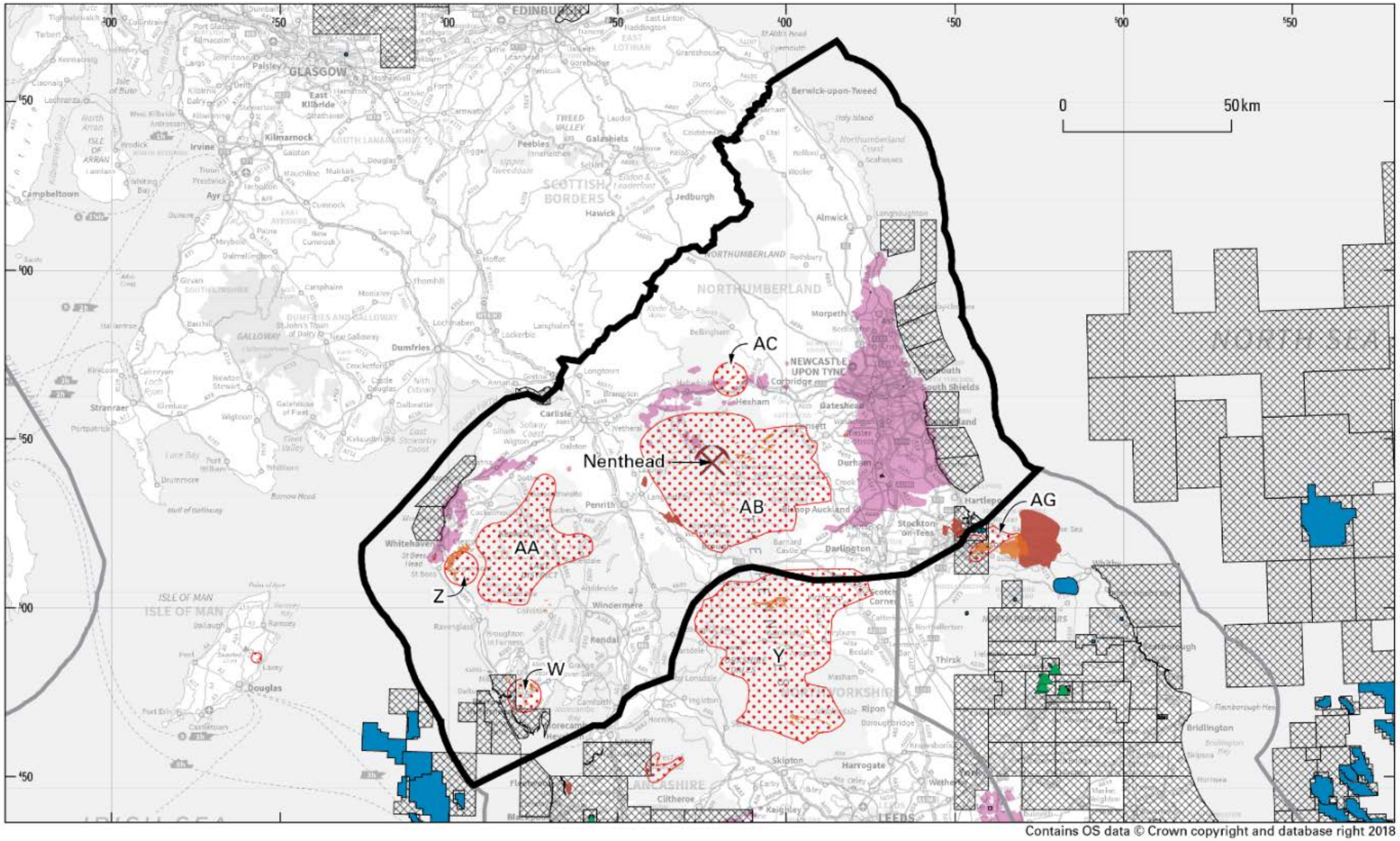

Figure 22 Distribution of mineral resources in the Northern England region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields and underground gas storage licence areas are not shown. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

Orefield	Map Label
South Cumbria	W
North Pennine (Askrigg)	Y
West Cumbria	Z
Lake District	AA
Northern Pennine (Alston)	AB
Settlingstones	AC
Cleveland*	AG

Described in the Eastern England TIR*

Northern England and adjoining areas

Metal prospects

Areas of known mining over 100 m below NGS datum

Metallic and vein minerals

Evaporite minerals

Coal

Orefields

Oil and gas

Active oil and gas extraction sites

Hydrocarbon licences (as at July 2018)

Oil and gas fields

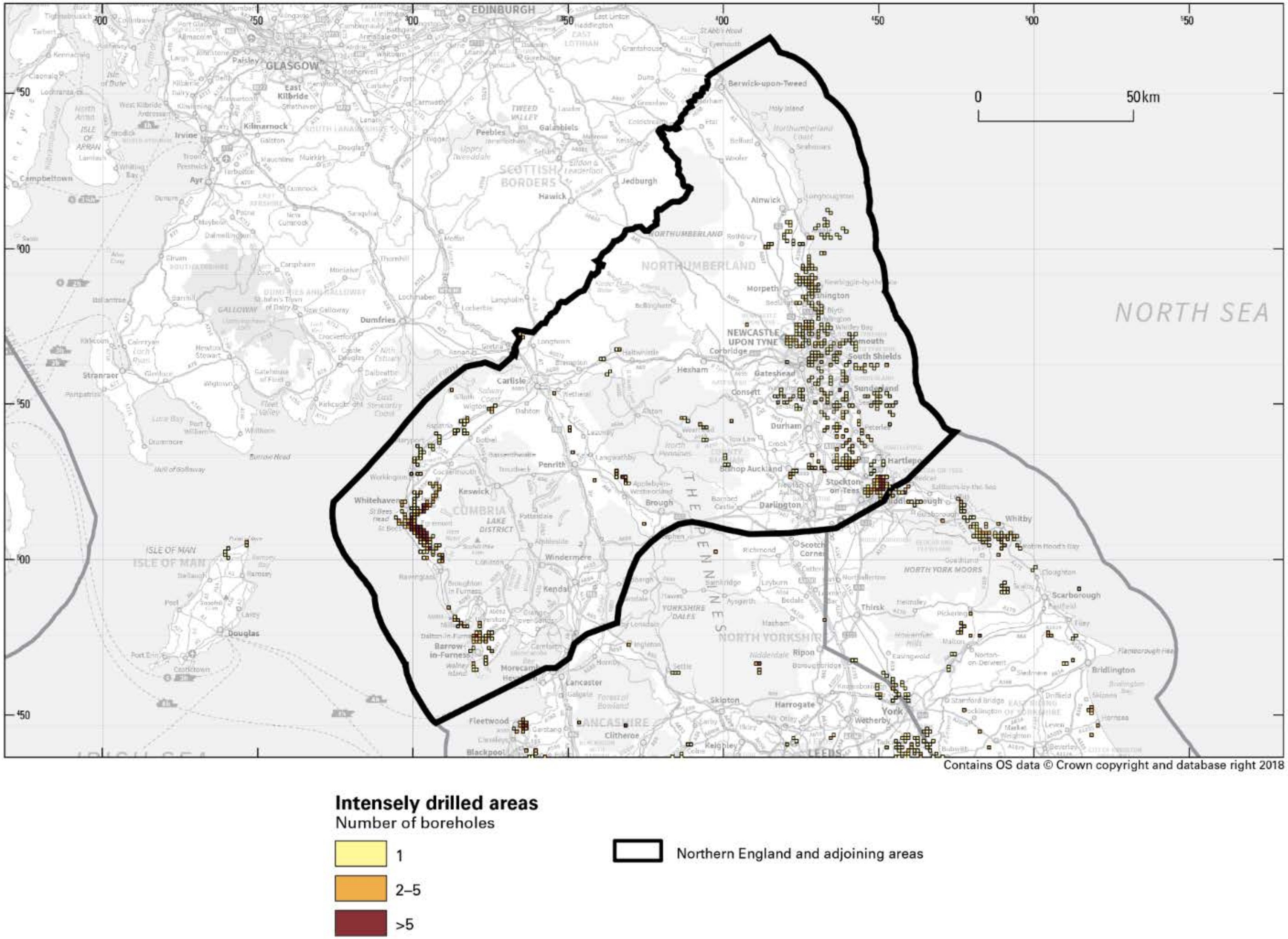

Figure 23 Location of intensely drilled areas in the Northern England region, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

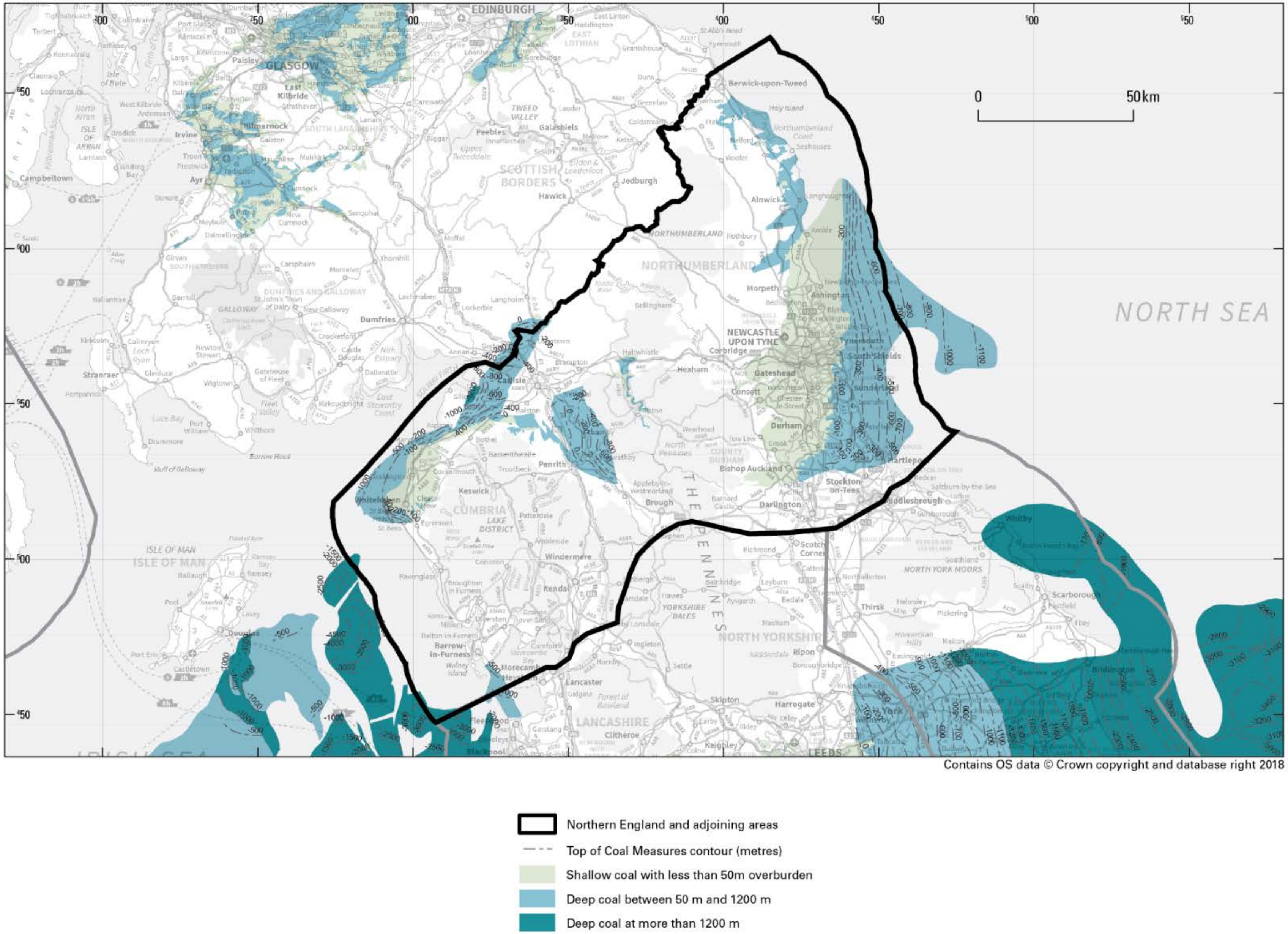

Figure 24 Distribution of coal resources in the Northern England region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

8.11 SUPPORTING INFORMATION

The location of deep mines is based on mine plans, reported locations and depths of historic mines, mapped mineral veins and areas of mineralisation. Mining has taken place in the UK since Roman times. With such a long history, mines may exist which have not been identified and therefore included within the comprehensive review used to create this dataset. However, it is unlikely these mines will be sufficiently deep to be of concern for NGS. It is also possible that mapped mineral veins do not accurately present the subsurface extent of underground workings. A buffer of 100 m has been applied to all mapped mineral veins to mitigate for this.

8.11.1 Mine depths

Any reported mine depth is often difficult to attribute to a specific datum. This results in a degree of uncertainty about the maximum depth of workings. For example, depths are variously reported as being from surface or adit (or adits) but it is often unclear which is being used and in which area of a mine. Significant additional research, including of historic mine plans and records, would be required to overcome this. A pragmatic solution to this issue has been to assume that reported depths are to the bottom of the deepest adit unless otherwise stated. Adits were driven from nearby valleys and another reasonable assumption is that adit level is approximately equal to NGS datum at the mine site.

Many mine shafts are not vertical or are vertical for only part of their total depth. For the purposes of this assessment it has been assumed that all depths are vertical. This will slightly overestimate depths where this is not the case.

Mine workings have been grouped in clusters where they are known or likely to be interconnected at depth through common workings or vein structures and the maximum known depth for the group of mines has been applied.

Most mine shaft depths are quoted in fathoms, some in feet and a few in metres. The conversion factors used in this assessment are:

1 fathom = 6 feet
1 foot = 0.3048 metres

Depths in metres have been rounded to the nearest whole metre.

There is frequently uncertainty about actual depths of shafts. Where more than one depth is quoted the deepest depth has been used unless there is evidence that this was an error. Again this will be conservative and present an overestimate of actual depth.

8.11.2 Mined extents

The areas of vein-type and related ore deposits shown on Figure 22 have been depicted where possible by applying a 100 m-wide buffer to the mapped extent of the mineral vein. Where this is not possible, a 100 m buffer has been applied the location of known mines in order to encompass the possible extent of the workings. This approach ensures that any inaccuracies in the mapped vein locations and extent of past workings fall within the boundary of the area identified.

Mine workings have been grouped into clusters where there are many worked veins that are known or likely to be interconnected at depth through common workings or vein structures and the maximum known depth for the group of mines has been applied. This allows for uncertainties in mine working interconnectivity and for interconnected groundwater flow pathways within the vein and associated structures.

8.11.3 Potash, halite, gypsum/anhydrite and polyhalite deposits

The extent and distribution of these bedded evaporite deposits is largely based on geological interpretation supported by seismic survey information and sparse boreholes. As such there is uncertainty about their distribution, which in some areas may be considerable.

8.11.4 Hydrocarbons (oil and gas)

The hydrocarbon fields displayed on Figure 22 are provided by the hydrocarbon industry to the Oil and Gas Authority. They represent the extent of known hydrocarbon resources usually shown by the oil or gas contact with water within the hydrocarbon trap structure.

The hydrocarbon licence areas displayed on Figure 22 represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place.

The approach adopted for exploration and the detailed evaluation of hydrocarbon resources prior to and during exploitation has resulted in the location, extent and depth of conventional hydrocarbon reservoirs being very well constrained. Conversely, the extents, depths and contained resource of unconventional (shale) gas and oil deposits is less well constrained. The distribution of the prospective rock types is based on geological factors (see Rock Type for discussion on these) and the potential of this type of deposit in any particular location is dependent on a number of factors such as past burial depth, organic content of the rocks and the practicality of extraction, none of which have been evaluated in the region.

8.11.5 Coal and related commodities

In many coal mining areas the coal seams are associated with other commodities that may also have been worked underground from the same mines, either with the coal or from separate geological horizons. These commodities include iron ores, ganister (a high silica material used in furnace lining construction etc.) and shale (for brick making). Such commodities are not considered separately here because the coal mining defines the areas and depths of past mining.

Information relating to the depth and distribution of 19th century and later coal mining is generally comprehensive and accurate, more so for workings dating from the mid-19th century onwards when mining legislation was enacted. The location and extents of older coal workings is less well constrained because records are incomplete or non-existent. However, most of these workings are shallow, rarely reaching depths in excess of 100 m below NGS datum. There is some uncertainty about the depth and distribution of deep unworked coal because this has not been mined. In many areas it is well constrained by information from seismic surveys and boreholes that were undertaken to assess coal resources and thus is well constrained but this is not always the case.

8.11.6 Borehole depths

Not all boreholes are drilled vertically. Some are inclined and others, mainly for hydrocarbon exploitation, are deviated, sometimes with multiple boreholes branching from a single initial borehole. The boreholes databases used records borehole length and not vertical depth. The BGS Single Onshore Borehole Index (SOBI) database also includes a number of boreholes that were drilled from mine galleries, mostly in coal mines, to evaluate coal seams in advance of mining or to assess higher or lower seams. For the purposes of preparing the borehole map it has been assumed that all boreholes are vertical and drilled from the surface. Depth calculations based on these assumptions will tend to be conservative, slightly over estimate maximum depth and will occasionally include or exclude a borehole if collared underground.

The borehole datasets use a ‘best estimate’ of the actual position, especially for earlier boreholes the location of which was determined using the then available technologies. The accuracy of individual grid references reflects the precision of the location. In some cases this is to the nearest 1 km grid square (in which case the grid reference is that of the south-west corner of the grid square in which it falls). However, as digital capture of locations developed (e.g. via use of GPS) more precise grid references were recorded. To accommodate any uncertainty in the location of a borehole a ‘location precision’ field in the data attribute table is included to indicate the certainty with which the grid reference was determined (e.g. 'Known to nearest 10 metres').

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The BGS holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at https://envirolib.apps.nerc.ac.uk/olibcgi

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Borehole locations

The locations of deep boreholes are from the BGS Single Onshore Borehole Index database (SOBI). Offshore borehole locations have been sourced from BGS offshore borehole database and DECC records for drilling for hydrocarbon exploration.

Geothermal energy resources

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Hydrocarbon resources

The locations of onshore and offshore oil and gas licences are available via the DECC website (https://www.gov.uk/topic/oil-and-gas), underground coal gasification licences are available via the Coal Authority website. (http://mapapps2.bgs.ac.uk/coalauthority/home.html).

Information on the locations of prospective areas for shale gas and oil has been sourced from the BGS/DECC regional shale gas studies: http://www.bgs.ac.uk/shalegas/