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National Geological Screening: the Pennines and adjacent areas

Minerals and Waste Programme

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BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/102

National Geological Screening: the Pennines and adjacent areas

C Waters[1], D Schofield[1], D E Evans[2], R Haslam[2], S Loveless[3], A Butcher[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, J R Ford, H Holbrook, I Longhurst and L Hannaford

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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
email scotsales@bgs.ac.uk

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 Pennines and adjacent areas 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 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 Pennines and adjacent areas (or 'the Pennines' in this report) region (Figure 1).

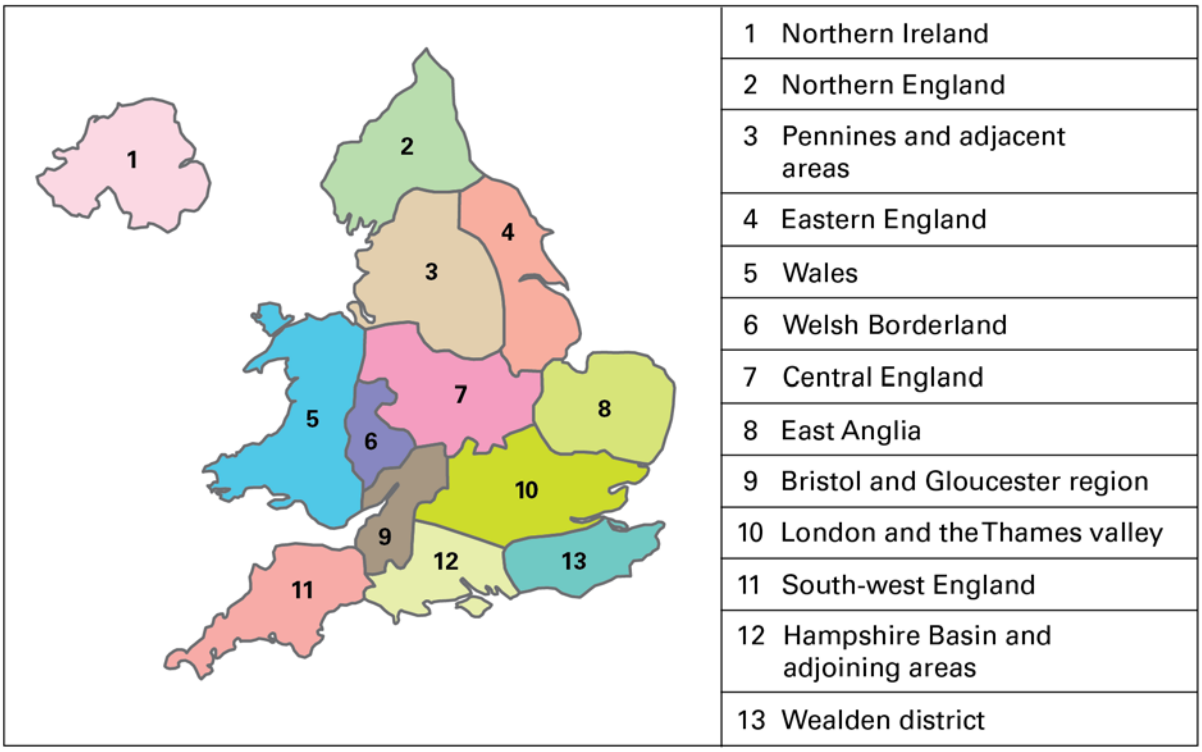


Figure 1 The BGS region boundaries as defined by the Regional Guides series of reports (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html). British Geological Survey © UKRI 2018.

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

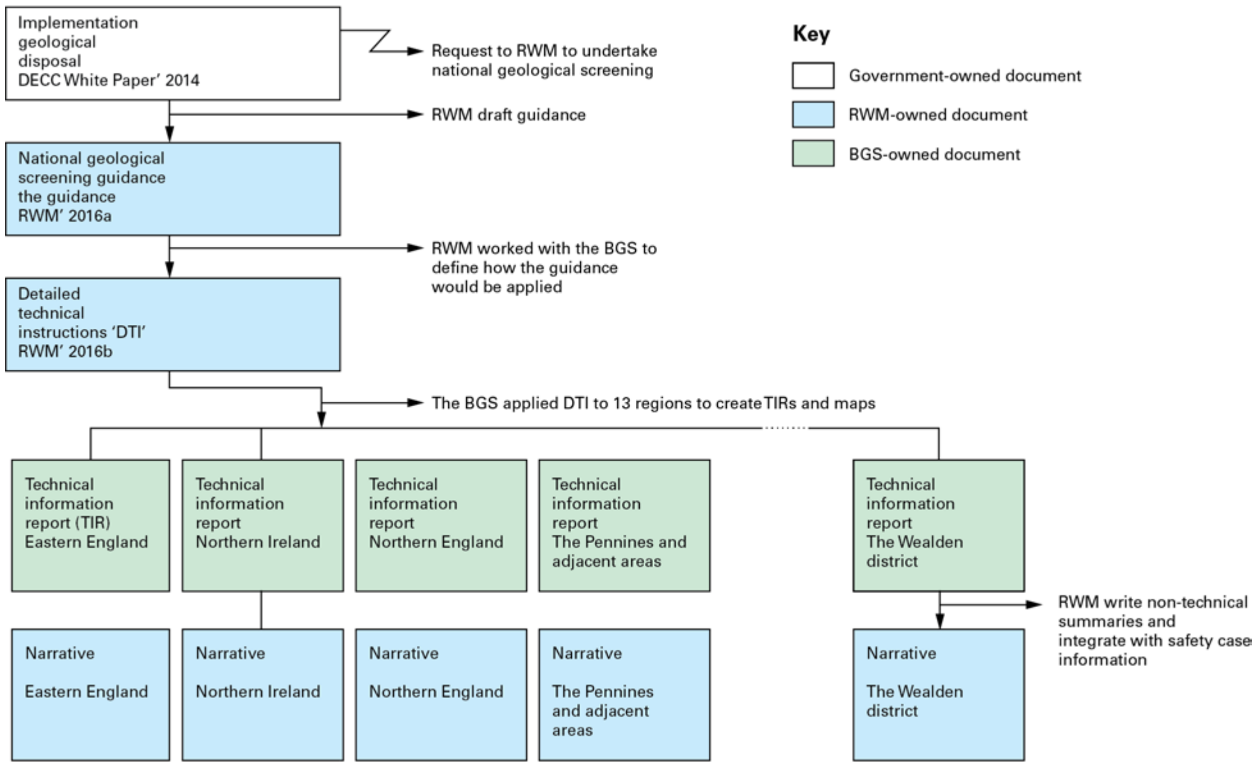


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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 Pennines region

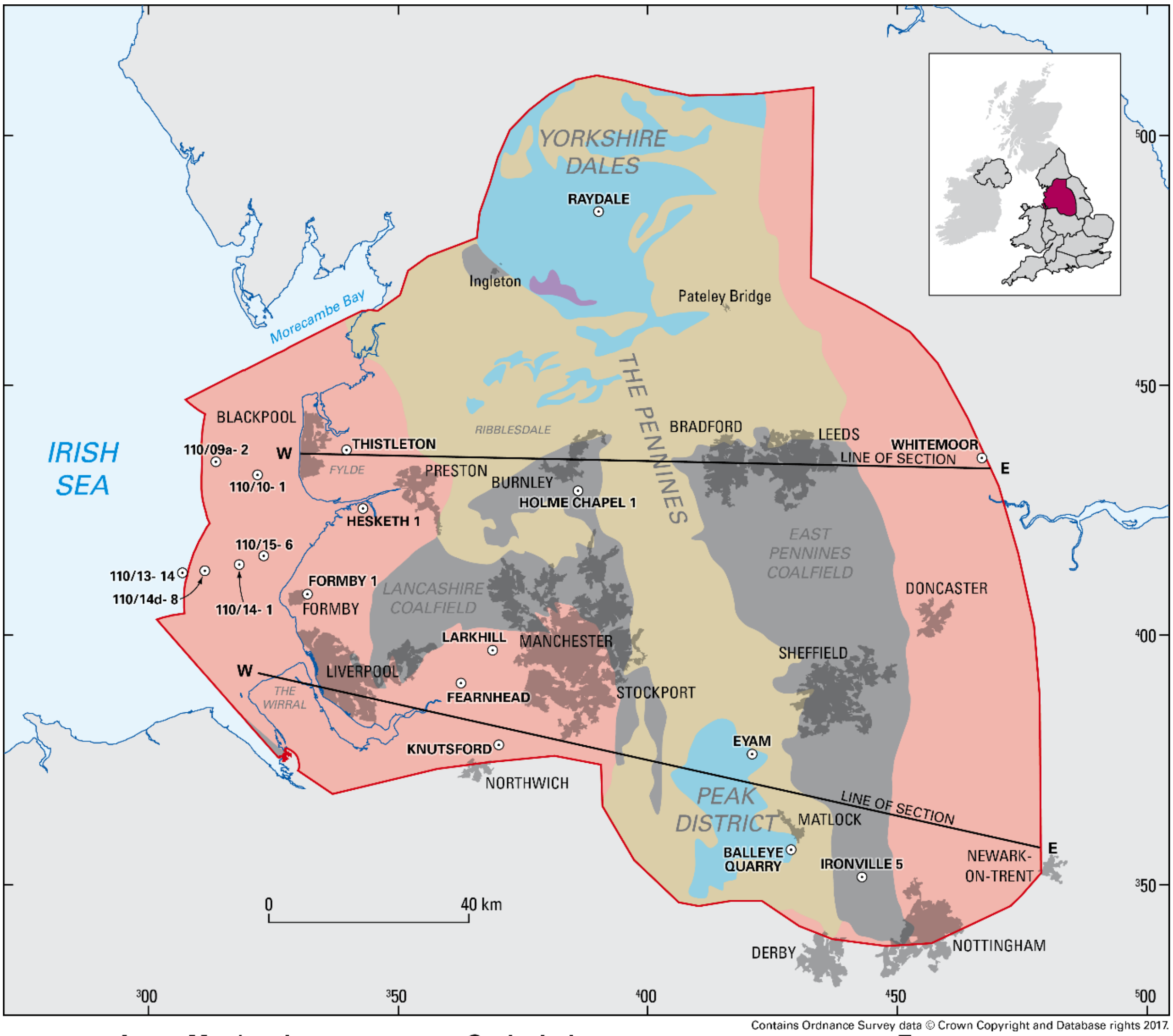
The Pennines region covers the upland areas of the Pennines from the Yorkshire Dales to the Peak District and the lowlands to both the west and east. It includes the large conurbations of Greater Manchester; Merseyside; the Lancashire towns including Preston and Burnley; the South and West Yorkshire cities of Bradford, Leeds and Sheffield; Derby, and Nottingham (Figure 3). The region's diverse landscape strongly reflects the composition and structure of the underlying bedrock geology. The strata seen at surface in the region are dominated by sedimentary rocks of Triassic, Permian and Carboniferous age, shown in Figure 3. The western and eastern margins of the region are underlain by Triassic and Permian rocks that show a downward passage from mudstone-dominated to sandstone-dominated formations. Halites (rock-salt) are common within the Triassic mudstones in the west of the region and limestones occur in the basal part of the Permian succession in the east. Industrial and urban developments that flank the southern part of the Pennines are centred on the coal-bearing mudstones and sandstones of the late Carboniferous-aged Coal Measures. The Yorkshire Dales and Peak District uplands are underlain by sandstones, mudstones and limestones of earlier Carboniferous age.

Underground mines and exploration boreholes, particularly for coal, provide confidence on the nature of the subsurface geology within the coalfield areas. Boreholes for water and hydrocarbons exploration, together with seismic surveys for the latter, inform an understanding of the subsurface geology of the western and eastern parts of the region. The subsurface distribution of the Craven Group and Carboniferous Limestone Supergroup is mainly based upon seismic data, with relatively few boreholes proving the successions. The lithological variability of early Palaeozoic sedimentary rocks is poorly constrained as those deep boreholes that reach the unit tend to penetrate only the uppermost few metres of strata. The presence of the Wensleydale granite is proved by a single borehole, but the lateral extent and depth of the intrusive body is comparatively poorly constrained through geophysical (gravity) modelling.

3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

The geology at surface in the region is shown in Figure 3 and Figures 4 and 5 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. Principal structural elements of the region are shown in Figure 6.

Geologically, the region can be broadly subdivided into a series of depositional basins, typically associated with thicker and more complete sedimentary successions, and blocks in which thinner and less complete successions predominate. Key basins within the region are: the East Irish Sea and east Deemster basins, located offshore of the Lancashire coast and affecting Permo-Triassic rocks; the Cheshire basin, located south-west of Manchester and also associated with deposition of Permo-Triassic rocks, and the Craven basin, extending across the central parts of the region, and the Stainmore basin of the extreme north of the region, both affecting Carboniferous strata. The main structural blocks include the Askrigg block, located in the Yorkshire Dales and influencing Carboniferous and older strata, and the Formby Point platform of west Lancashire, affecting Permo-Triassic rocks. Numerous smaller blocks and basins affect the buried Carboniferous geology, e.g. the central Lancashire, Askern–Spital and Derbyshire highs, to name a few. The rocks in the region are predominantly sedimentary in origin.



Age (Ma)	Map/section descriptor	Geological sub-units		Text descriptor
200–270	Permo-Triassic sedimentary rocks	Mercia Mudstone Group Sherwood Sandstone Group Cumbrian Coast Group Appleby Group Zechstein Group Rotliegendes Group		Younger sedimentary rocks
305–360	Carboniferous sedimentary rocks	Warwickshire Group Pennines Coal Measures Group		Older sedimentary rocks
		Millstone Grit Group Craven Group		
		Carboniferous Limestone Supergroup		
420–480	Early Palaeozoic–Neoproterozoic	Various Palaeozoic and older sedimentary and igneous rocks		Basement rocks

Figure 3 Generalised geological map and key showing the distribution of younger sedimentary rocks, older sedimentary rocks and basement rocks in the onshore Pennines region. The inset map shows the extent of the

region in the UK. See Figures 4 and 5 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 therefore 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 public sector information licenced under the Open Government Licence v3.0. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

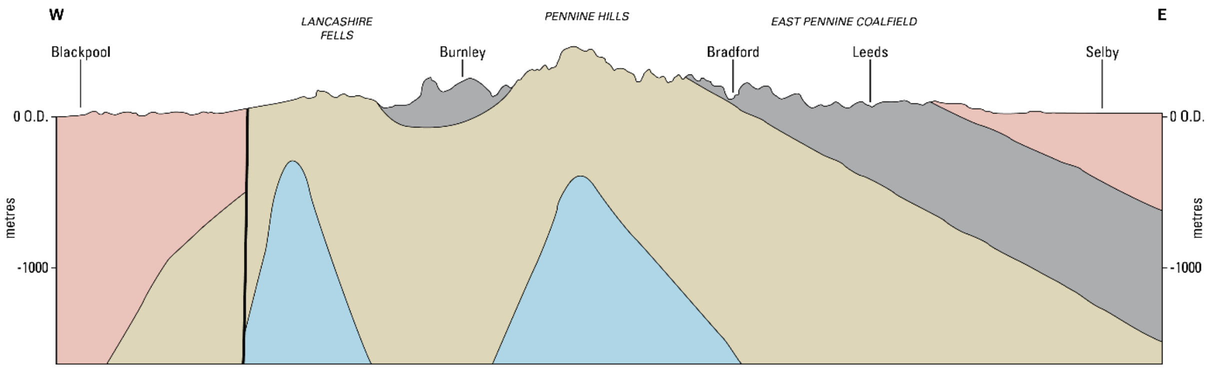


Figure 4 Northern west–east schematic cross-section through the Pennines region. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

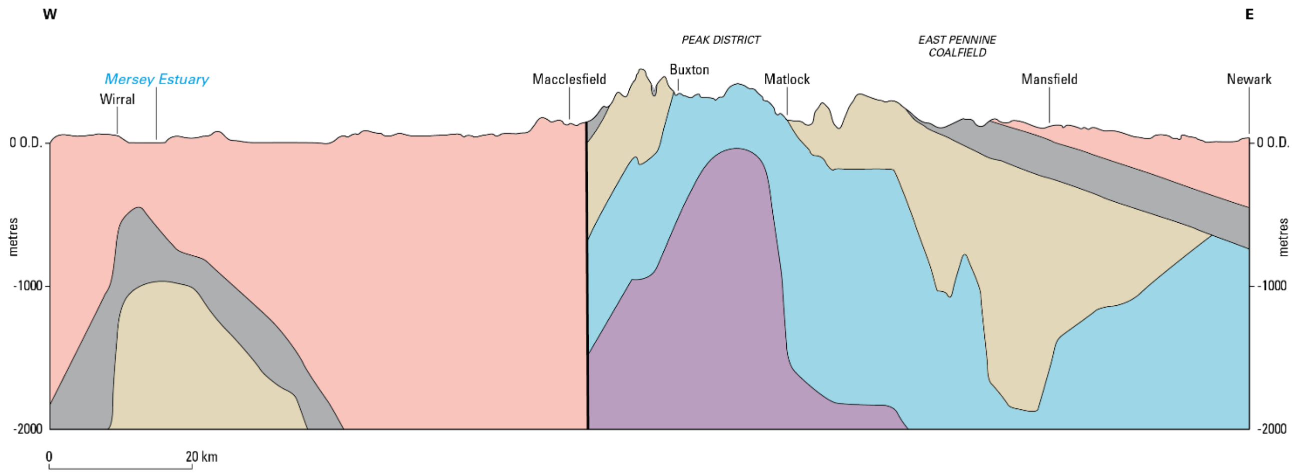


Figure 5 Southern west–east schematic cross-section through the Pennines region. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

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 on the basis of process of 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 PENNINES REGION

A generalised vertical section (GVS) for the Pennines region is presented in Table 3 identifying the PRTIs that occur between 200 and 1000 m below NGS datum. The geological units are generally shown in stratigraphical order. However, due to regional variations, some units may be locally absent or may be recognised in different stratigraphical positions from those shown. Only those units identified as PRTIs are described. Principal aquifers are also shown and are described in Section 6.

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

The majority of the basement rocks in the region, comprising early Palaeozoic sedimentary rocks, lie outside established cleavage belts, east of the Wales Caledonian cleavage front and south of the Lake District Acadian cleavage front (see PRTI criteria in Table 2) and it is not known whether the mudstone component of these rocks, proved in boreholes and inferred from geophysical and gravity data, preserves a pervasive cleavage and, therefore, is sufficiently compacted and metamorphosed. Consequently they are not considered to be a PRTI and are not considered further. Early Palaeozoic–Neoproterozoic mudstones occurring in the north of the region and within the Lake District cleavage front are considered as PRTIs where they occur within the depth range of interest. Various igneous rocks (basaltic lavas, breccias and intrusive dolerites) in the Peak District are relatively thin, are not explicitly modelled in UK3D and form only a minor component of the parent unit. They are therefore not included as PRTIs and not described.

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 BGS Regional Guide to the Pennines and Adjacent Areas (Aitkenhead et al., 2002) 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 UK3D 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.

Maps showing the distribution of PRTIs between 200 and 1000 m below surface, amalgamated into the generic host-rock types (i.e. EVAP, HSR and LSSR), are provided in Figures 6, 7 and 8 respectively. A further map showing the combine lateral extent of all PRTIs is provided in Figure 9.

4.2.1 Confidence in the geological interpretations

Many aspects of the extent and composition of the deeper rocks have variable degrees of uncertainty across the region. This is dependent upon the type of data available, such as boreholes, seismic reflection data and potential field (gravity and aeromagnetic) data. Boreholes typically provide good to excellent certainty on the elevation of lithological boundaries at the position of the borehole, but modelled certainty in the position of these boundaries decreases away from the borehole positions. Geophysical techniques carry varying degrees of confidence. Seismic reflection data, generally acquired during hydrocarbon and coal exploration, provide resolution of principal boundaries, particularly of unconformities, which can be tied to key boreholes and allows extrapolation of these boundaries over large areal extents. Seismic reflection data coverage varies in both the density and quality of data across the region, in part related to the vintage of differing surveys but also to the prospectivity of the subsurface strata. Principal uncertainties in seismic interpretation depend on the spacing and quality of the seismic grid, migration (or not) of the data and depth conversion of the interpretation. Potential field (gravity and aeromagnetic) data are the least sensitive techniques on which to base interpretations, with only marked contrasts in lithologies able to be identified and mapped with considerable degrees of uncertainty to the elevation of boundaries.

The Permo-Triassic and underlying Carboniferous rocks present in the west (west Lancashire) and east (Nottinghamshire–Yorkshire lowlands) of the region have the best density of seismic reflection data coverage, whilst areas underlain by basement massifs and Tournaisian–Visean intrabasinal highs to the north and south of the region have no coverage due to their lack of hydrocarbon prospectivity. In these areas, confidence in the location of subsurface boundaries is relatively low. The lithological variability of early Palaeozoic and older sedimentary rocks is also poorly constrained, as those few deep boreholes that reach the units tend to penetrate only the uppermost few metres of strata. The presence of the Wensleydale granite, beneath the Yorkshire Dales, is proved by a single borehole, but the lateral extent and depth of the intrusive body is comparatively poorly constrained through geophysical (gravity) modelling. Areas of younger older-cover rocks (Namurian–Westphalian strata) have generally poor coverage, except where underlain by thicker Tournaisian–Visean basin successions east of the Pennines.

There are numerous deep boreholes (greater than 200 m below NGS datum) in the region (see Figure 23), mainly drilled for the evaluation of the coal deposits on both sides of the Pennines, for the evaluation of salt and development of gas storage caverns in the west of the region, and for both conventional and unconventional hydrocarbon exploration and exploitation. The areas of highest intensity of drilling are around Southwell, Nottinghamshire and Preese Hall, Lancashire, with over 50 boreholes/km^2 in some areas. Over the coalfield areas there are rarely more than 5 boreholes/km^2 but the majority of the coalfields have been intensively drilled. Where available, borehole data from water and hydrocarbons exploration inform a good understanding of the subsurface geology. In the offshore area of the Irish Sea, the interpretation of seismic reflection data is not publically available, and for NGS3D subsurface geometries are largely constrained by released borehole/well data and a limited amount of interpreted seismic data appearing in journals.

In addition to boreholes, underground mines, particularly for coal, provide confidence on the nature of the subsurface geology of Westphalian strata within the south Lancashire and east Pennines coalfield areas.

Table 3 Schematic GVS for the Pennines 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. Permian Cumbrian Coast Group and Appleby Group occur in the west of the region while Zechstein Group and Rotliegendes Group occur in the east. See Figures 6, 7 and 8 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	Triassic	Mercia Mudstone Group	Mudstone with local siltstone and evaporite deposits of anhydrite, gypsum and halite	N/A	Mercia Mudstone Group	Northwich Halite Mb, Warton Halite Fm, Preesall Halite Mb/Fm, Mythop Halite Mb, Rossall Halite Mb, Fylde Halite Mb	N/A
YOUNGER SEDIMENTARY ROCKS	Triassic	Sherwood Sandstone Group, Lenton Sandstone Formation	Sandstone with conglomerate	N/A	N/A	N/A	Sherwood Sandstone Group (Helsby Sandstone Fm, Wilmslow Sandstone Fm, Chester Fm including St Bees Sandstone Mb)
YOUNGER SEDIMENTARY ROCKS	Permian	Kinnerton Sandstone Formation	Sandstone	N/A	N/A	N/A	Kinnerton Sandstone Formation
YOUNGER SEDIMENTARY ROCKS	Permian	Cumbrian Coast Group	Mudstone, siltstone and sandstone with evaporites including halite	N/A	Barrowmouth Mudstone and Manchester Marls formations	St Bees Evaporite Formation	N/A
YOUNGER SEDIMENTARY ROCKS	Permian	Appleby Group	Red sandstone	N/A	N/A	N/A	Collyhurst Sandstone Formation
YOUNGER SEDIMENTARY ROCKS	Permian	Zechstein Group and Lenton Sandstone Formation*	Dolomitised limestone, dolostone and mudstone with varied evaporites (halites, polyhalites, sulphates, potash)	N/A	N/A	Fordon Evaporites Formation	Zechstein Group; Lenton Sandstone Fm* (Permo-Triassic and part equiv. to Zechstein Group)
YOUNGER SEDIMENTARY ROCKS	Permian	Rotliegendes Group	Sandstone, breccia and conglomerate	N/A	N/A	N/A	Rotliegendes Group
OLDER SEDIMENTARY ROCKS	Carboniferous	Warwickshire Group	Siltstone and sandstone with subordinate mudstone and coal	N/A	Salop, Halesowen and Etruria formations	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Pennine Coal Measures Group	Mudstone, siltstone, sandstone, coal and ironstone	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Millstone Grit Group	Sandstone, siltstone and mudstone	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Craven Group	Mudstone with sandstone and limestone	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Carboniferous Limestone Supergroup	Limestone with interbedded mudstone, locally mafic lava and mafic tuff	N/A	N/A	N/A	Carboniferous Limestone Supergroup
BASEMENT ROCKS	Lower Palaeozoic–?Neoproterozoic	Silurian rocks (undivided) = Windermere Supergroup (part)	Mudrock with siltstone and sandstone	Horton Fm, Crummack Fm, (Stockdale Gp)/ Windermere Supergroup	N/A	N/A	N/A
BASEMENT ROCKS	Lower Palaeozoic–?Neoproterozoic	Unnamed igneous intrusion, Ordovician	Granite	Wensleydale granite	N/A	N/A	N/A
BASEMENT ROCKS	Lower Palaeozoic–?Neoproterozoic	?Ordovician – Neoproterozoic rocks (undivided) = Windermere Supergroup (part) Ingleton Group	Weakly metamorphosed slate and sandstone	Dent Group	N/A	N/A	N/A

*Lenton Sandstone Formation is separate unit sitting directly below the Sherwood Sandstone Group. Although not formally part of the Zechstein Group, it is combined with the Zechstein group in NGS3D. Note, however the Lenton Sandstone Formation is described together with the Sherwood Sandstone Group in the groundwater section of this report.

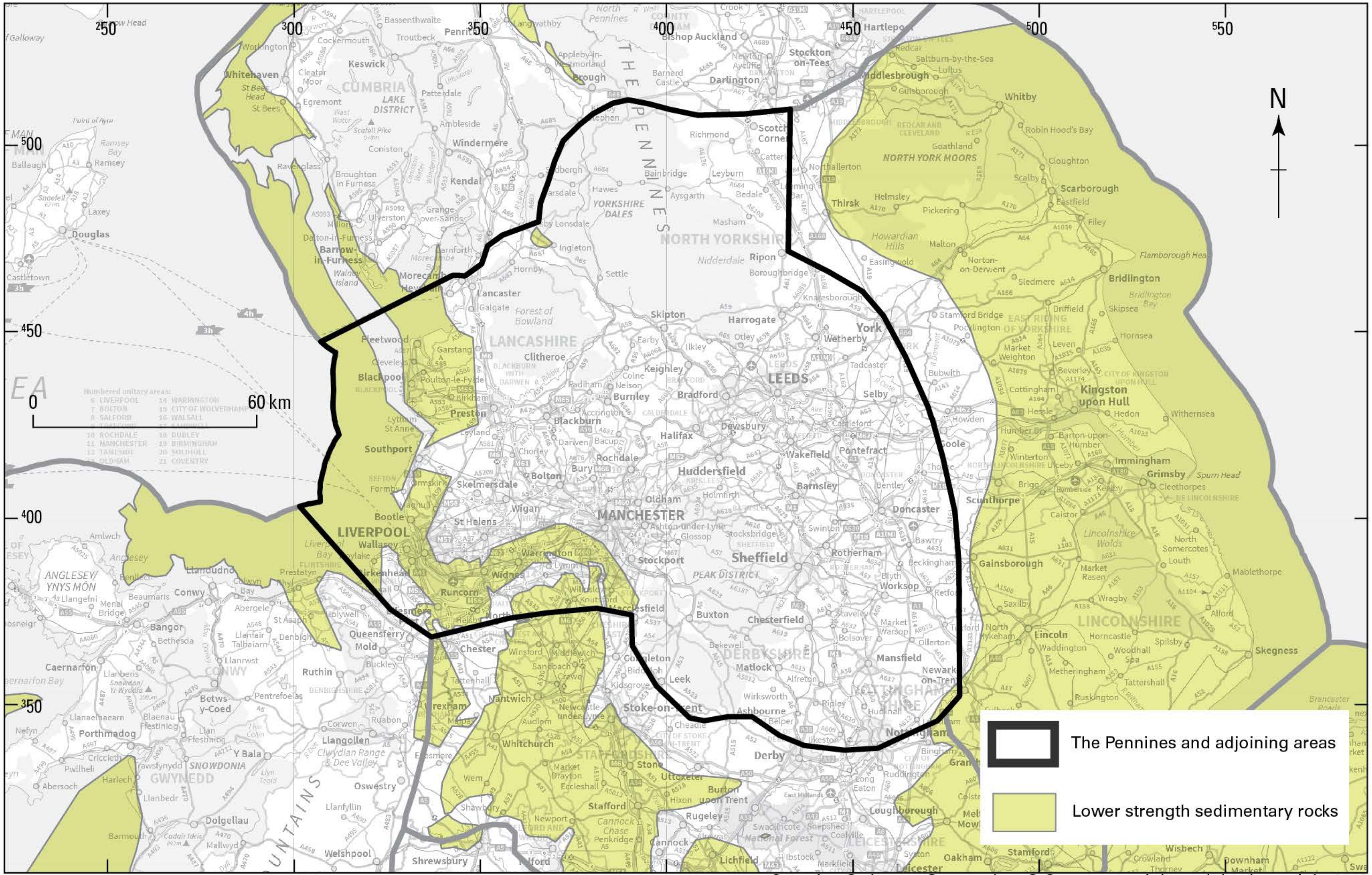


Figure 6 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Pennines region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

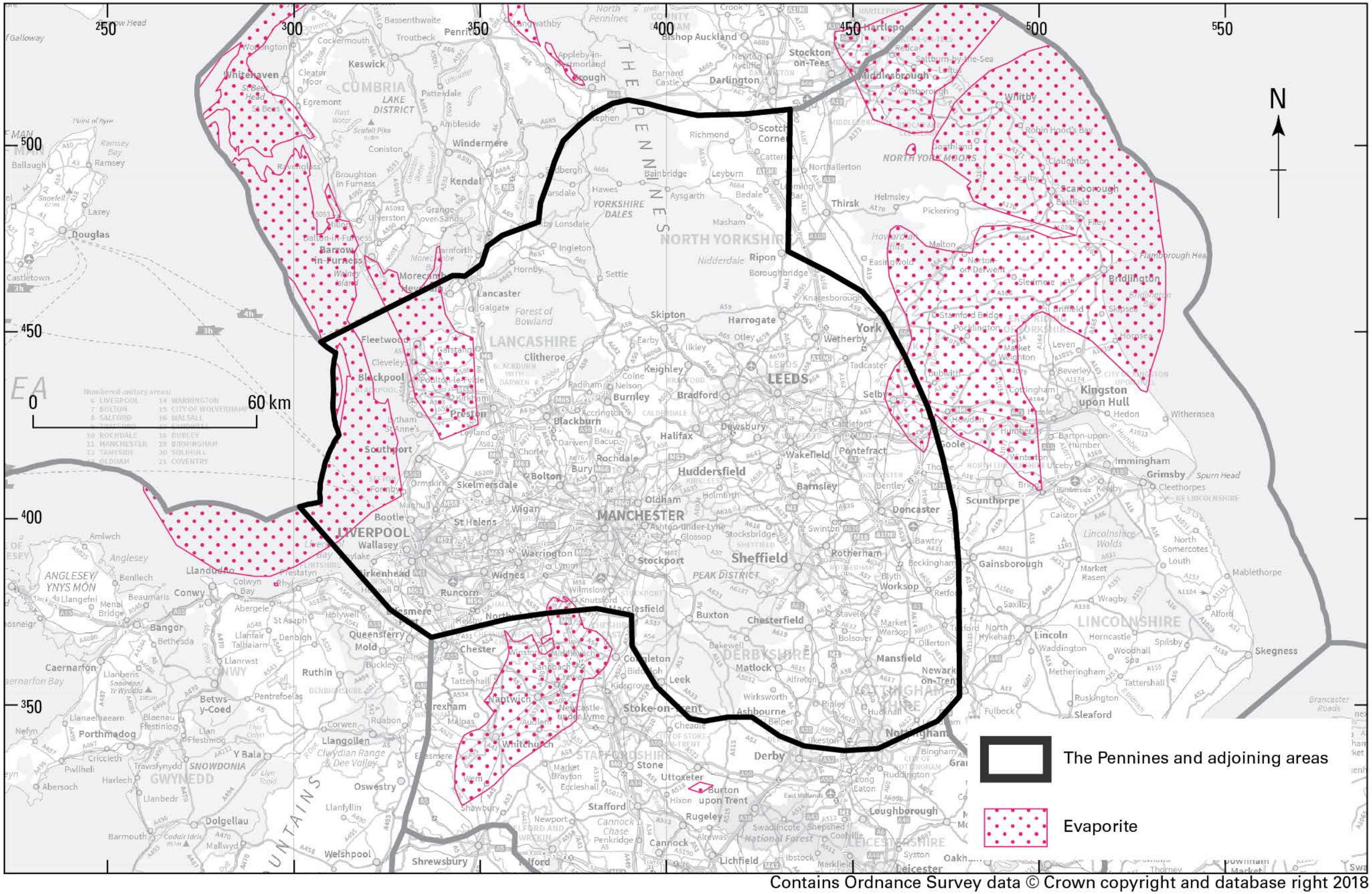


Figure 7 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the Pennines region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

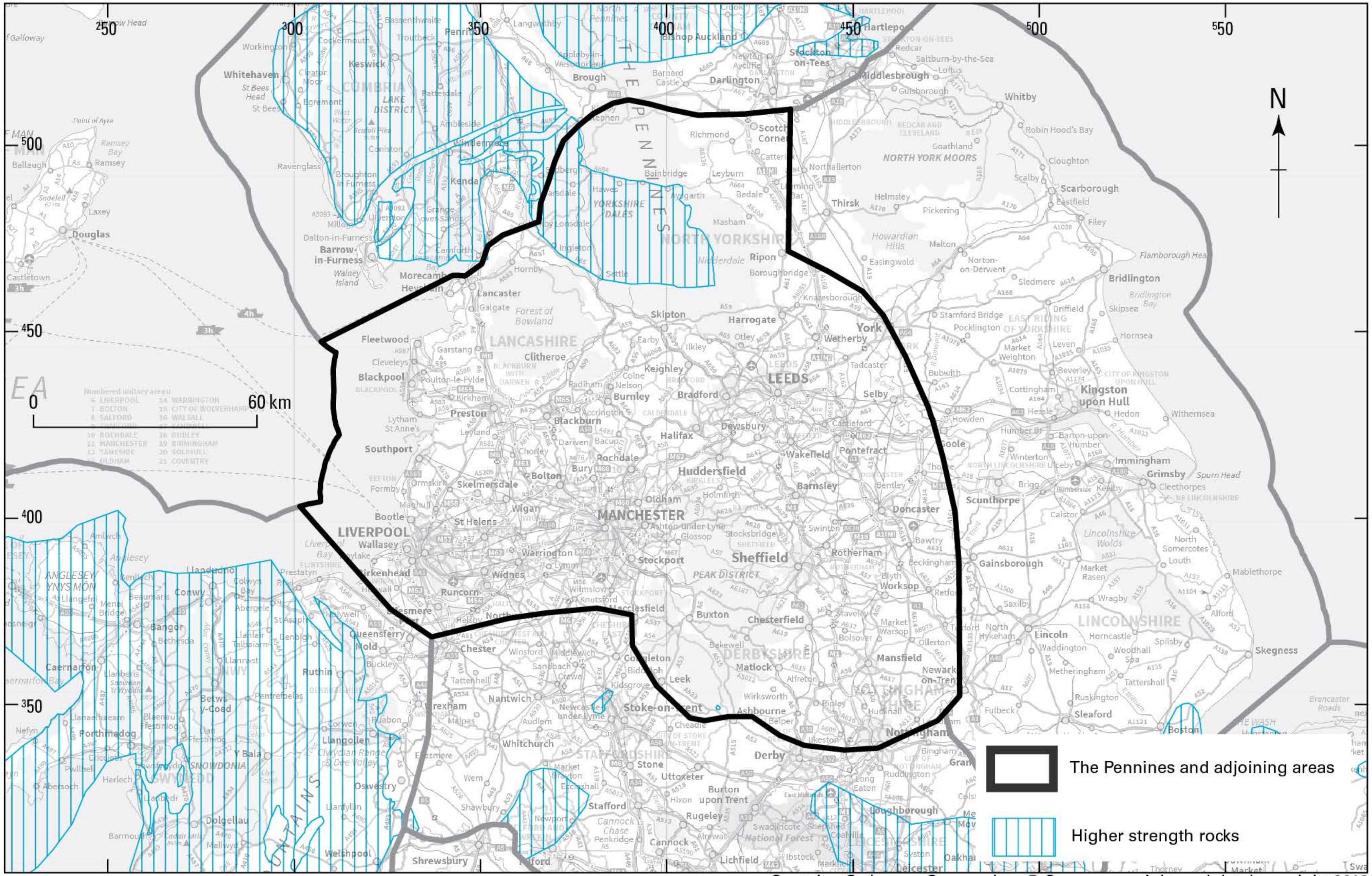


Figure 8 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Pennines region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

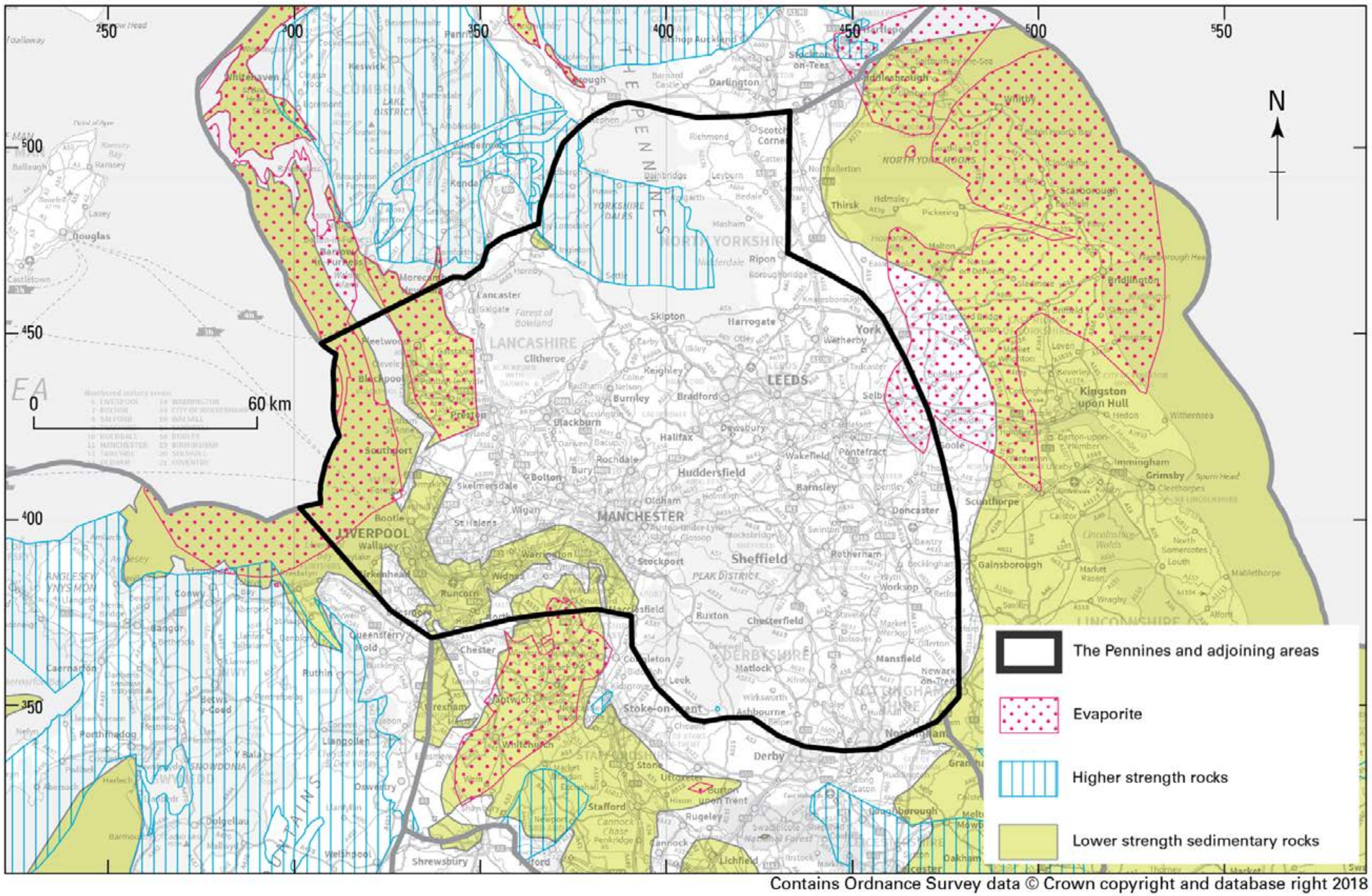


Figure 9 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Pennines region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

4.2.2 Younger sedimentary rocks

4.2.2.1 MERCIA MUDSTONE GROUP — LSSR AND EVAP

The Mid to Late Triassic-aged Mercia Mudstone Group provides a mudstone-dominated PRTI. The Mercia Mudstone Group is proved in the lowland plain of west Lancashire (400 m thick near Blackpool and 600 m at Formby) and extension offshore in East Irish Sea basin, and Greater Manchester in the Cheshire basin (1200 m thick). It is also present at outcrop in the south-east of region from east of Doncaster to Newark, where it is up to 190 m thick but, with the exception of the extreme south-east, is too shallow to be of interest. The overlying Penarth Group, which is not shown as a separate unit in the model, is not present within this region, occurring just beyond the southern and south-eastern margins (Aitkenhead et al., 2002).

Three halites occur within the depth range of interest onshore in the Fylde area around Blackpool, west Lancashire (Figure 10). These are, in descending order: the Preesall Halite Member (up to 180 m), Mythop Halite (14–35 m) and Rossall Halite (0–15 m thick) members (Aitkenhead et al., 2002). The Rossall and Mythop halites both thin eastwards in the Fylde and are absent in the eastern extent of the group (Wilson and Evans 1990). Offshore, an additional two halites (Jackson and Johnson, 1996) include the Warton Halite Formation (up to 269 m), present towards the top above the Preesall Halite Member, and the Fylde Halite Member (up to 182 m), present in the lower part of the group below the Rossall Halite Member (Figure 10). The Warton Halite Member is only present within the depth range of interest in the extreme west of the region, offshore of the Formby coast, proved in Borehole 110/14d-8 (Figure 3) to a depth of 356 m. The Preesall Halite Formation (equivalent to the onshore Preesall Halite Member) is modelled to occur within the depth range of interest offshore of the Fylde, west of Borehole110/10-1 and offshore of the Formby coast, notably in boreholes 110/13-14, 110/14d-8 and 110/15-6. The Mythop and Rossall halite members occur within the depth range of interest west of the Formby coast, in boreholes 110/13-14, 110/14-1 and, for the lower unit only, 110/15-6, but occur at depths greater than the depth range of interest within a downfaulted graben proved by Borehole 110/14d-8. In the Cheshire basin, the Wilkesley Halite Formation (up to 404 m; equivalent of the Warton Halite Formation of Lancashire) and the older Northwich Halite Formation (up to 283 m) form extensive halite units with considerable thickness variations (Aitkenhead et al., 2002), although only the latter unit is present within the depth range of interest north of Northwich.

Principal information sources

Onshore, exposures of the group are rare and much of the information concerning the Mercia Mudstone Group succession comes from deep boreholes. However, none of the boreholes shown in the NGS3D model includes the presence of the five main halite units; information on these halites is from outside the region from boreholes within the Irish Sea. The extent of mapped halite formations present at crop, from the DigMap50k dataset, was used to constrain their surface position. However, the solubility of halite beds results in their absence from the zone of mobile groundwater and the mapped extent actually represents a subcrop known as ‘wet rockhead’. As wet rockhead occurs at shallower depths than the depth range of interest (between 200 and 1000 m below NGS datum, for this study) this issue has no bearing on the final modelled distribution within the depth range of interest. In places, the mapped extent of halites disagrees with the boreholes, partly as the boreholes post-date the mapping, but also because the mapping shows outcrop at the wet rockhead at an unconstrained depth rather than at true rockhead. The boreholes were given priority in such a circumstance. Offshore, reliance is placed upon borehole information and interpretation of 2D seismic data largely from outwith the study area; Jackson and Johnson (1996) provides maps showing the inferred distribution of the halites (Figure 10).

Offshore of the Fylde, the Mercia Mudstone Group occupies the east Deemster basin of Jackson et al. (1995), bounded to the west by the East Deemster Fault and to the east by the Formby Point Fault. The offshore hydrocarbons Borehole 110/10-1 proves the base of the group at 501.7 m depth, with the base modelled as deepening to the west to a maximum of 1105 m below OD. On the Formby Point platform, present to the east of the Formby Point Fault and extending across the onshore part of the Fylde, the base of the group is much shallower, proved at a depth of 100.57 m in the Thistleton Borehole (Figure 3), but modelled to depths of about 390 m below OD around the coastline. Further south, off the Formby coast and within the east Deemster basin, the depth of the group is borehole constrained by the offshore boreholes 110/13-14 (to 952.2 m depth); 110/14d-8 (to 1362.46 m); 110/14-1 (to 1062.53 m), and 110/15-6 (to 797.36 m). To the east, on the Formby Point platform, the base of the group is much shallower, modelled to a depth of about 260 m below OD. The Formby 1 Borehole, located on the Formby Point platform, confirms the shallow depths for the base of the group, which is here seen at 79.24 m depth.

Within the Cheshire basin, there is a broad deepening of the base of the group towards Northwich, within the axis of the basin. In the Knutsford Borehole the base of the group is at 753.0 m depth, south of which it is modelled extending to about 1050 m below OD.

The Preesall salt field in the Blackpool area was worked via brine pumping until 1993 (Aitkenhead et al., 2002) and structure contours for the base of the Preesall Halite Member and isopachytes for this member are shown in Wilson and Evans (1990) and reproduced in Figure 11. These are based upon almost a hundred boreholes used to characterise the salt field. The Northwich Halite Formation is commercially exploited by mining and controlled brine pumping in the region, leaving cavities about 100 m in diameter and up to 170 m high. The thickness of the Northwich Halite Formation, including the south-western part of this region, is shown by Plant et al. (1999) and is presented in Figure 12. Note that the thickness shown on this plot includes the Knutsford Borehole and the thickness shown on this figure disagrees with the current interpretation.

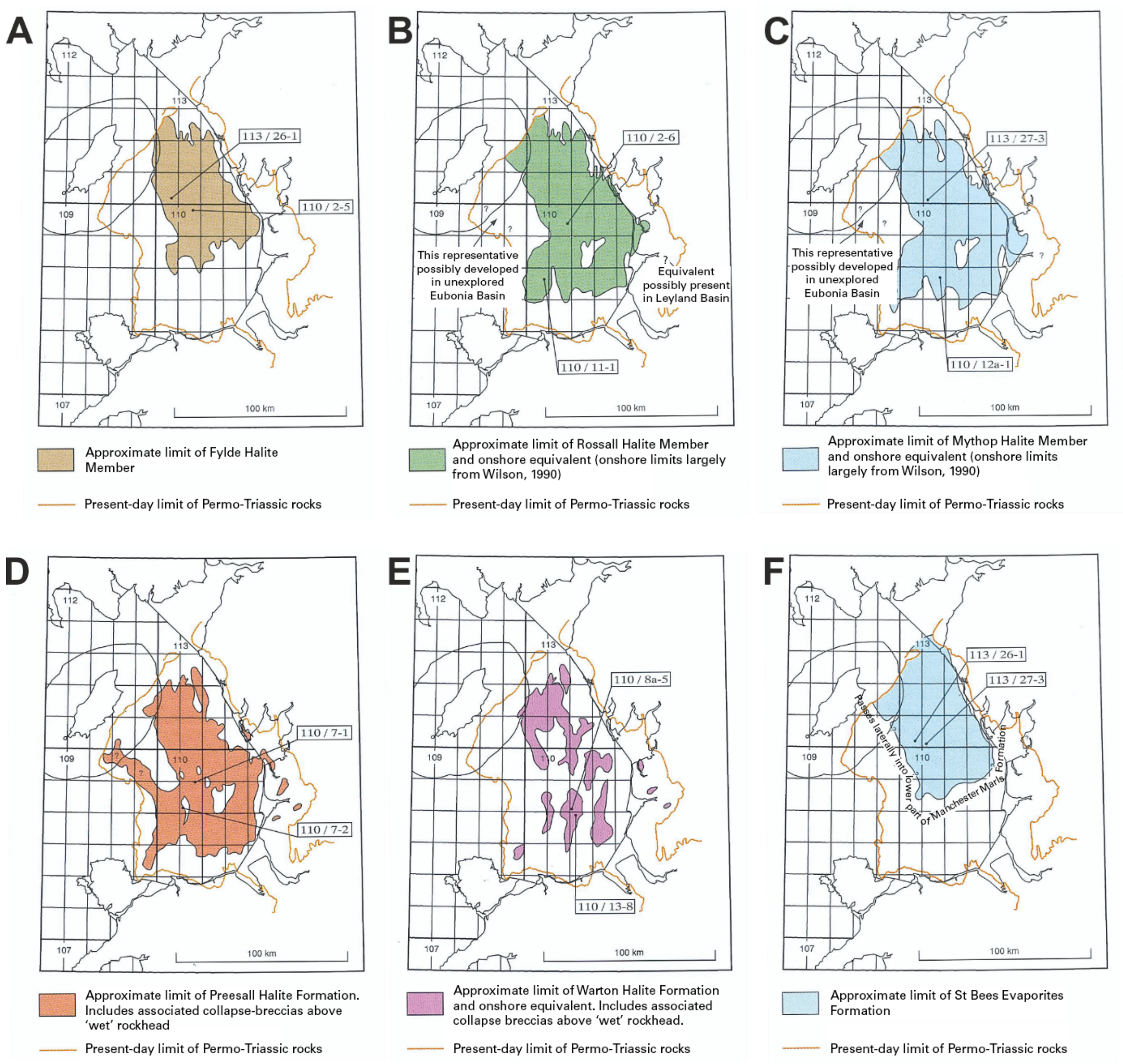


Figure 10 Distribution of the five principal halites recorded in the East Irish Sea: A) the Fylde Halite Member; B) the Rossall Halite Member; C) the Mythop Halite Member; D) the Preesall Halite Formation; E) the Warton Halite Formation, and F) the St Bees Evaporite Formation (from Jackson and Johnson, 1996). British Geological Survey © UKRI 2018

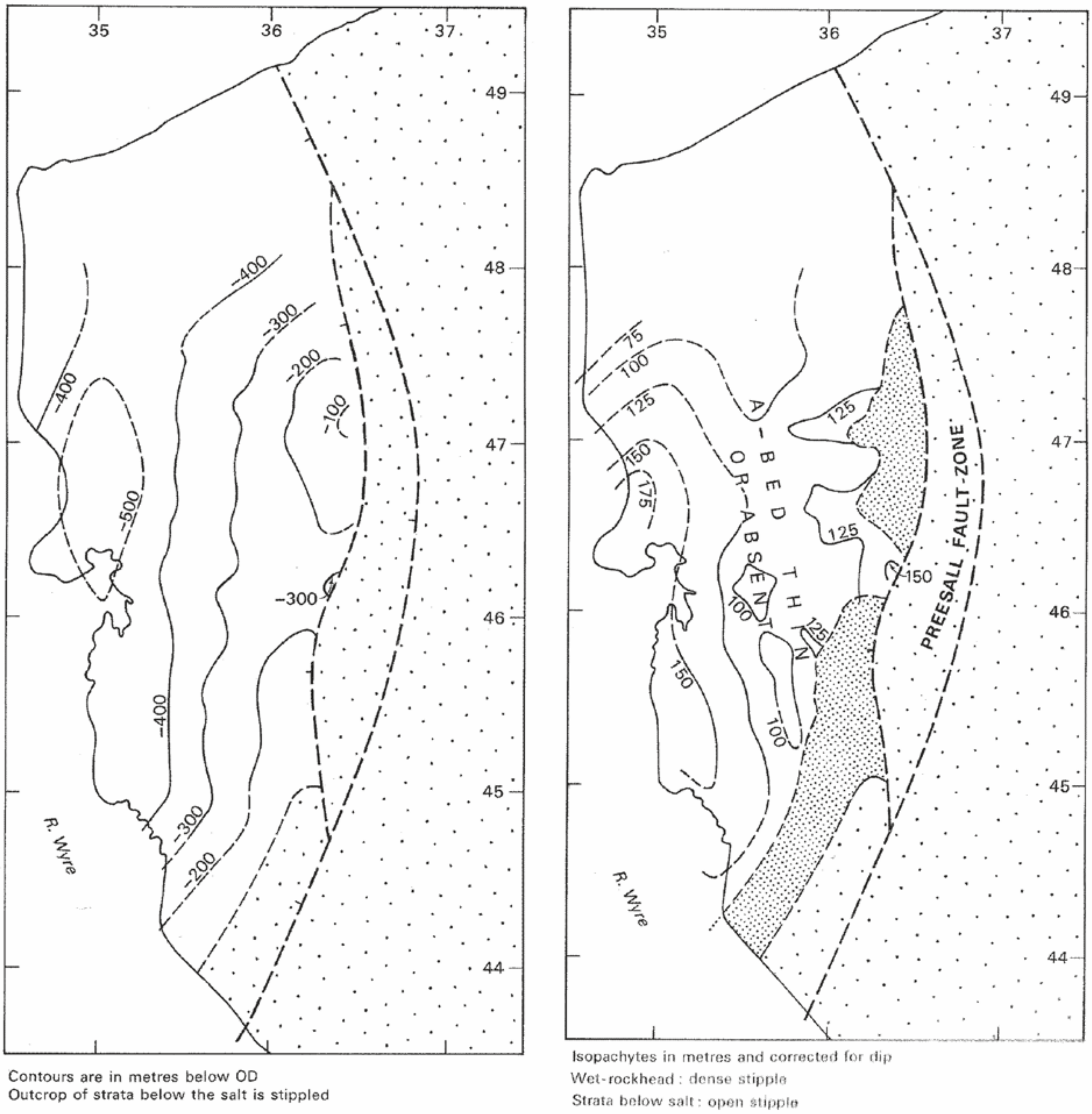


Figure 11 Structural contours for the base of the Preesall Halite Member and isopachytes for the member, corrected for dip (from Wilson and Evans 1990). British Geological Survey © UKRI 2018

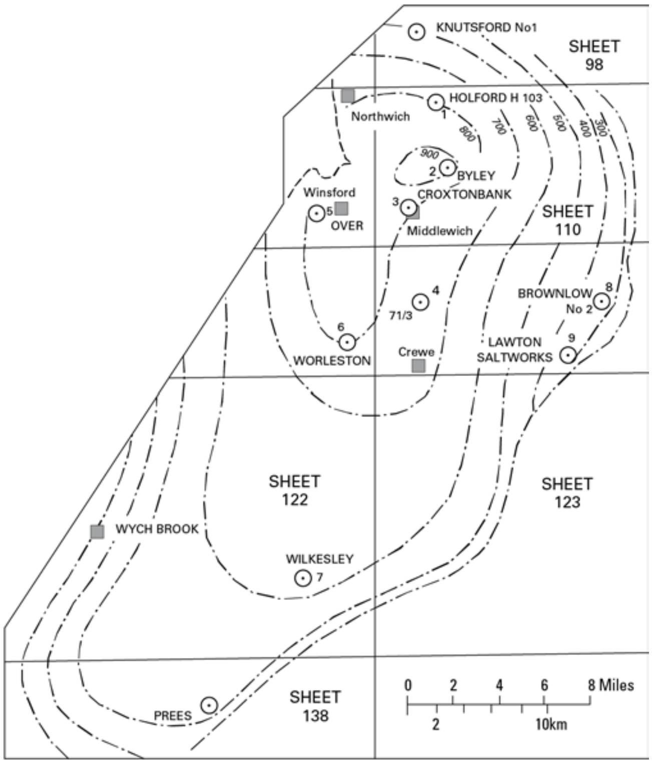


Figure 12 Isopachytes (in feet) for the Northwich Halite Formation (from Plant et al., 1999). British Geological Survey © UKRI 2018

Rock type description

In west Lancashire, the Mercia Mudstone Group is represented by the Sidmouth Mudstone Formation; higher mudstone units (Branscombe Mudstone and Blue Anchor formations) are absent. The Sidmouth Mudstone Formation comprises, in descending order (Wilson and Evans 1990): reddish-brown, structureless mudstone with gypsum in the middle part and a brecciated upper part in total 209 m thick (Breckells Mudstone Member; revised to formation status by Howard et al., 2008); reddish-brown mudstone interbedded with greenish-grey mudstone beds less than 1 m thick in a succession up to 129 m thick (Coat Walls Mudstone Member; obsolete term, now equivalent to the upper part of the Kirkham Mudstone Member of Howard et al., 2008); the Preesall Halite Member; the Thornton Mudstone Member (obsolete term, now equivalent to the lower part of the Kirkham Mudstone Member of Howard et al., 2008) of up to 113 m of interlaminated mudstone and siltstone with alternating greenish-grey and reddish-brown cycles; the Mythop Halite Member; red-brown, mainly structureless mudstone with impersistent beds of halite (Singleton Mudstone Member); the Rossall Halite Member, and a basal 30 m-thick succession of medium grey, micaceous, interlaminated mudstones and siltstones, the latter making up to about 20 per cent of the sequence (Hambleton Mudstone Member).

The Mercia Mudstone Group in the Cheshire basin (south-western) part of this region, between Northwich and the Knutsford Borehole, comprises within the depth range of interest mainly red-brown mudstone and siltstone with green mottling, spots and beds, with thick halite (Northwich Halite Formation) and anhydrite beds in the upper part and pink, fine-grained sandstone interbeds common in the lower part (the lowermost 60–90 m of the Tarporley Siltstone Formation) (Aitkenhead et al., 2002). The Blue Anchor Formation, which forms a green, dolomitic mudstone at the top of the group, is only present above the depth range of interest within the Cheshire basin part of this region (Aitkenhead et al., 2002).

Offshore, the Warton Halite Formation in the Irish Sea consists mainly of clean halite beds up to 12 m thick (exceptionally up to 20 m) with numerous, laterally persistent, red-brown or brown mudstone partings on average 3 m thick, but up to 12 m (Jackson and Johnson, 1996). A thickness of 284 m is recorded in Borehole 110/14d-8 (Figure 3) at a basal depth of 356 m, west of the Formby coast; the thickness off the Fylde coast is unknown. Offshore, the Preesall Halite Formation comprises clean halite with thin partings of red-brown or pale brown mudstone and grey-brown siltstone (typically less than 3 m), 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 around 100 m on blocks (Jackson and Johnson, 1996). Onshore, in the Fylde area the formation is thickest (greater than 150 m) in the axis of the Preesall Syncline and in the hanging wall of the Preesall fault zone (Figure 11).

The Mythop Halite Member comprises individual leaves of halite ranging in thickness from l m to 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 51.5–241.5 m in thickness (Jackson and Johnson, 1996) but thins towards the Fylde coast, and onshore the succession is more mudstone-dominated with either halite veins or halite beds up to 2 m thick (Wilson and Evans 1990).

The Rossall Halite Member consists of leaves 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 member is up to 148 m thick, with thinning to the east accompanied by progressive loss of the lower halites (Jackson and Johnson, 1996).

Within the East Irish Sea basin, the Fylde Halite Member generally comprises leaves 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). The member ranges up to 182.5 m in thickness (Jackson and Johnson, 1996). The member is shown to occur beneath Morecambe Bay and west of the Fylde (Jackson and Johnson, 1996; Figure 4), without indication of the depth. Given that no section within the NGS3D model crosses the shown extent of the unit, the unit has not been modelled. It is possible that the unit occurs in the depth range of interest in the extreme north-western offshore part of the region in an area already shown to include Preesall Halite Formation and potential halites in the Cumbrian Coast Group.

4.2.2.2 Cumbrian Coast Group — LSSR and EVAP

Within the offshore East Irish Sea basin, west of Morecambe Bay and north and west of the Fylde, the Cumbrian Coast Group includes the Barrowmouth Mudstone Formation underlain by a basal St Bees Evaporite Formation (Figure 10F). The offshore Barrowmouth Mudstone Formation typically ranges in boreholes from 83–135 m in thickness (Jackson and Johnson, 1996). The thickness, determined from offshore boreholes, of the St Bees Evaporite Formation may be more than 200 m (Jackson et al., 1987), particularly where the formation is dominated by halite. Farther south offshore, and extending across the onshore, the group is represented by the Manchester Marls Formation. The group is present onshore in the lowland plain of west Lancashire in the Fylde and Formby areas (120 m thick in the latter), although in both it is present only in the subsurface and its distribution is known only from deep boreholes. Around Greater Manchester, in the Cheshire basin, the group is present at crop and is proved in the subsurface in the Knutsford Borehole (up to 150 m thick) as the Manchester Marls Formation.

Principal information sources

The group, evident as the Manchester Marls Formation, has been proved offshore in Borehole 110/09a-2 (from 1213.1 to 1385.0 m) (Figure 3), but in other boreholes occurs below maximum penetration depths. Therefore for all, or most, of the east Deemster basin of Jackson et al. (1995) the group occurs below the depth range of interest. West of Morecambe Bay, there are no boreholes to constrain the depth of the Barrowmouth Mudstone and St Bees Evaporite formations and hence their elevation is poorly constrained in this area, but is considered likely to be below the depth range of interest. Onshore, on the Formby Point platform of west Lancashire, the group is proved in the Thistleton (818.95 to 926.24 m), Hesketh 1 (563.54 to 660.46 m) and Formby 1 (990.55 to 1078.93 m) boreholes, broadly occurring at shallower levels to the east. In the Cheshire basin, the group is proved in the Knutsford Borehole (from 2117.5 to 2265.5 m), well below the depth range of interest, but the unit shallows to the west, north and east of this borehole to levels of interest around the periphery of the basin, where it is also occurs at crop. The interpretation of seismic data has permitted modelling of the basal unconformity (the Variscan unconformity) of the group by Smith et al. (2005).

Rock type description

The offshore St Bees Evaporite Formation is characterised by 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). The overlying Barrowmouth Mudstone Formation comprises red-brown, generally calcareous, silty mudstone and anhydrite mudstone, interbedded with, and passing laterally to, orange-brown to red-brown, micaceous, typically calcareous siltstone (Jackson and Johnson, 1996).

Offshore, the Manchester Marls Formation consists of mainly red-brown to red mudstones with subordinate red-brown or grey-green, micaceous siltstones, together with sporadic beds of red-brown to yellow-white sandstone, ranging from fine to coarse-grained. The formation may be up to 227 m thick, and anhydrite with dolostone and/or limestone is notably present as a basal carbonate unit about 25 m thick (Jackson and Johnson, 1996). In addition, halite occurs in the north in the lateral transition to the St Bees Evaporites Formation. Onshore, the mudstones are commonly calcareous, occurring interbedded with siltstone and thin beds of fossiliferous, marine limestone and dolostone. In the Cheshire basin, the formation becomes increasingly more arenaceous towards the top (Freshfield Sandstone Member), which thickens towards the south of the East Irish Sea, north of the Wirral. The Manchester Marls Formation becomes more arenaceous towards the west and the south, being represented by sandstones of the Bold Formation in the western Cheshire basin (Aitkenhead et al., 2002).

4.2.2.3 ZECHSTEIN GROUP — EVAP

The Permian Zechstein Group crops out in the east of the region from Nottingham to Doncaster, Harrogate and Ripon, dipping eastwards below the Sherwood Sandstone Group and occurring within the depth range of interest along much of the eastern boundary of the region. The Zechstein Group rocks are highly variable both laterally and vertically. At depth in the region, the rocks consist of major cycles of limestone and dolomite, mudstone, siltstone and sandstone followed by variable sulphates (e.g. anhydrite, gypsum) and halides (e.g. halite) (Smith, 1974). Only the lowest halite, considered to be the equivalent of the Fordon Evaporite Formation of the Eastern England region, is present within the depth range of interest between York and Selby. Halite is subject to plastic flow at depth, which may result in contortion and rapid lateral changes in thickness. Around Ripon and Harrogate, dissolution of interbedded evaporite minerals causes substantial variation in the thickness of the group at crop (Smith, 1974).

Principal information sources

Knowledge of the distribution and lithology of the Zechstein Group is derived mostly from exploration boreholes for hydrocarbons. The key boreholes used in NGS3D generally occur within the Eastern England region to the east, close to the eastern edge of the Pennines region. 21.46 m of halite are proved in the Whitemoor Borehole (Figure 3), the base of which is present at 397.02 m below NGS datum. The presence of the Fordon Evaporite Formation within the region is derived from the NGS3D model from the adjacent Eastern England region.

Rock type description

The Fordon Evaporite Formation is about 20 m thick in the concealed eastern part of the region (Smith, 1974). In the Selby area, the halite commonly occurs as veins and nodules and is described as having a 'ragged discontinuous mesh of mudstone, siltstone and anhydrite, and appears to be wholly secondary' (Smith, 1974).

4.2.3 Older sedimentary rocks

4.2.3.1 WARWICKSHIRE GROUP — LSSR

The Warwickshire Group (formerly termed 'Ardwick Group' in this region) occurs at crop along the northern margin of the Cheshire basin and occurs extensively at depth within the basin. The group is subdivided into two units: the siltstone and sandstone dominated upper Salop Formation and the mudstone dominated lower Etruria Formation, with an intervening heterogeneous succession (Halesowen Formation) of mudstone, siltstone and sandstone, with coals.

The Salop Formation has not been proved in the region (Aitkenhead et al., 2002), but is modelled along with the Etruria Formation (65–145 m thick) to be present in the subsurface in the south-west of the region from the Wirral to Manchester and southwards into the Cheshire basin. Mudstones are particularly prevalent in the lower part of the Salop Formation and throughout the Etruria Formation. The Etruria Formation rests conformably upon strata of the Pennine Coal Measures Group and is overlain by an unconformity at the base of the Cumbrian Coast Group. This unconformity removes some or all of the components of the Warwickshire Group.

The Halesowen Formation (up to 200 m thick), is present in the depth range of interest in the south-west of the district from the Wirral to Manchester. Mudstones are particularly prevalent in the upper part of the formation. This part of the group typically rests unconformably upon strata of the Etruria Formation elsewhere, but in this region is taken to be conformable.

There can be difficulties in distinguishing the Warwickshire Group from reddened rocks of the Pennine Coal Measures Group; the distinction relies upon petrographical and palaeontological evidence. 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 region in the east Pennine coalfield; west and south of Doncaster, and in the Lancashire coalfield between Liverpool and Manchester. For example, 331 m of red-stained strata in the Fearnhead Borehole (Figure 3) were originally interpreted as ‘Coal Measures’, but have been reinterpreted as Warwickshire Group on the common presence of limestones beds. The extent of the group east of the Pennines (Aitkenhead et al., 2012) differs from the modelled extent in NGS3D.

Principal information sources

The group occurs at crop along the northern margin of the Cheshire basin, from the east of Liverpool through Manchester to Stockport. It is also proved at depth within the Cheshire basin both in boreholes and through interpretation of seismic data, with the base of the group modelled by Smith et al. (2005). In the Knutsford Borehole (Figure 3) the interpreted Salop Formation is proved from 2821.5 to 2862.0 m and the Halesowen Formation proved to the base of the borehole at 3045.7 m. The group shallows towards the west, north and east of this borehole, occurring within the depth range of interest around the periphery of the basin. The group is proved in the Fearnhead Borehole from 641.71 to 849.0 m, comprising lithologies typical of the Halesowen Formation (mudstone, siltstone, sandstone, limestone and coal). The Larkhill Borehole (Figure 3) comprises a reddened succession interpreted as undivided Warwickshire Group from 436.02 to 524.0 m that could represent reddened Pennine Upper Coal Measures, which is proved below the reddened zone. Offshore, the group is not definitively proved in boreholes and its offshore extent is mapped only on seismic data, north of the Wirral.

Rock type description

The Halesowen Formation typically comprises mixed grey and varicoloured mudstones and siltstones with micritic limestones up to 4.9 m thick, thin coals, palaeosols, ironstones and dark grey shales (Aitkenhead et al., 2002), clearly observed in the lower part of the Knutsford Borehole. The Etruria Formation within this region (formerly the Ardwick Marls) comprises mainly mottled brown, red-purple, green and grey, poorly bedded mudstone and siltstone.

4.2.4 Basement rocks

4.2.4.1 UNDIVIDED SILURIAN ROCKS — HSR

Undivided Silurian rocks are modelled as present in NGS3D (as ‘Silurian mudstone’), but poorly constrained, beneath the Wirral–Liverpool and in a small area (less than 100 km^2) east of Pateley Bridge, both areas at depths much greater than the depth range of interest (typically greater than 2000 m and 1400 m below OD respectively). Within the Craven inliers of North Yorkshire (located immediately north of the North Craven Fault) the Silurian succession is not crossed by any NGS3D cross-sections, but the dominantly argillaceous Crummack and Horton formations of the Windermere Supergroup are proved at crop. However, these formations are unconstrained outside the area of crop and it is not known if they are present at depth.

Undivided Silurian rocks are not modelled in the Craven area. In this area, NGS3D shows a sedimentary unit classified as 'Ordovician mudstone'. The Crummack Formation (Stockdale Group) of Llandovery age occurs at the base of the Silurian succession, resting conformably upon a heterogeneous succession of siltstone and mudstone, with tuff, sandstone and conglomerate interbeds of the Sowerthwaite Formation (Dent Group) of Ordovician age. It shows passage upwards into the mainly sandstone turbidites of the Austwick Formation. The younger Horton Formation, of Ludlow age, has a top marked by a conformable passage into overlying, dominantly sandstone turbidites and the base by passage into underlying calcareous siltstones (Aitkenhead et al., 2002). Within the Craven inliers the base of the Windermere Supergroup rests unconformably upon the Ingleton Group (Kirby et al., 2000) and is overlain with an angular unconformity by Carboniferous strata.

Principal information sources

This unit is present at outcrop in the Welsh basin to the west of the region and is considered by Smith et al. (2005) to extend beneath Carboniferous strata in the Wirral–Liverpool area, although the unit is shown undivided with no indication of likely lithologies. No boreholes prove this succession and the extent is derived from seismic interpretation. The Silurian rocks in the Craven inliers of North Yorkshire are mainly proved from surface outcrop, not being proved in any of the boreholes present in the model.

Rock type description

The Crummack Formation comprises about 35 m of black, graptolitic mudstone and siltstone. Mudstones at the base of the formation are calcareous and contain a shelly fauna. Towards the top of the formation, greenish-grey, calcareous siltstones are generally cleaved and contain nodules and thin beds (0.1 to 0.45 m) of limestone (Arthurton et al., 1988).

The Horton Formation comprises medium to dark grey, laminated, micaceous and partly calcareous sandy siltstone or silty mudstone, with calcareous nodules present in layers near the base (Arthurton et al., 1988) and includes a unit of fine-grained, turbiditic sandstone present about 420 m above the base of the formation (Aitkenhead et al,. 2002). The formation is up to 710 m thick, and is openly folded and locally steeply dipping with a cleavage typically parallel to the west-north-west-trending fold axes (Arthurton et al., 1988).

4.2.4.2 UNNAMED IGNEOUS INTRUSION, ORDOVICIAN GRANITE — HSR

This unit includes the Wensleydale granite, emplaced during Caradoc times within the Askrigg block and proved in the Raydale Borehole (Figure 3) within the depth range of interest (Dunham 1974). Further granites shown in the subsurface within the Pennines are conjectural and occur at depths greater than the range of interest.

Principal information sources

The Wensleydale granite is proved in the Raydale Borehole at shallow depths from 495.05 m to the base of the borehole at 600.56 m (Dunham, 1974). This confirms the presence of the granite batholith that had been proposed through geophysical modelling to extend about 8.4 x 6.4 km, with an east–west axis, beneath much of the Askrigg block, due to the presence of a prominent negative gravity anomaly (Bott, 1967). The inferred mapped extent of the batholith and the extent that the granite subcrops the base of Carboniferous strata is derived from Kirby et al. (2000), which does not provide depth information.

Rock type description

The Wensleydale granite comprises, where proven in the Raydale Borehole, a pink, medium-grained, equigranular, unfoliated granite of potassium and albitic feldspar, quartz and chlorite. The latter replaces biotite during post-magmatic alteration, which is also associated with variable sericitisation of the K-feldspars and introduction of dolomite into veins and cavities (locally associated with sulphide mineralisation). In the borehole, the granite is strongly affected by near-vertical fractures accompanied by steep veins of quartz and carbonate at some levels (Kirby et al., 2000). An anastomosing, near-vertical cleavage is recognised in thin sections with discrete fractures spaced at intervals of 0.2 to 1 mm (Kirby et al., 2000). The nature and heterogeneity of the granite elsewhere in the intrusion is unknown.

4.2.4.3 UNDIVIDED ORDOVICIAN–NEOPROTEROZOIC ROCKS — HSR

This unit is modelled in NGS3D (as ‘Ordovician mudstone’) beneath the central and northern parts of the region. This unit is considered to be a PRTI in the northern part of the region in the Craven area, to the north of the Craven fault system where it occurs within the Lake District cleavage front and the depth range of interest.

The unit includes the oldest part of the Windermere Supergroup, the Dent Group. The Dent Group is divided into two formations in the Craven area: the Sowerthwaite Formation and the Norber Formation. The age of the Dent Group at crop in this area is Ashgill; older (Caradoc) beds are perhaps present at depth elsewhere in the region.

Older strata of the Ingleton Group (Neoproterozoic; Millward and Stone, 2012) occur in the Craven area in close proximity to the Dent Group inliers. The Ingleton Group is not modelled separately in NGS3D.

Principal information sources

Type sections for the component formations of the Sowerthwaite and Norber formations are designated in the Austwick area to the north-west of Settle. The concealed extent and character of the Dent Group in this area is relatively poorly constrained. The Beckermonds Scar Borehole located to the north of Settle indicates Ordovician Ingleton Group (Arenig), at a depth of about 530 m; regional studies incorporating available borehole data provide the primary constraint in NGS3D (Kirby et al., 2000).

The Ingleton Group consists of turbiditic sandstone and siltstone with sporadic intraformational conglomerate. It is not considered a PRTI.

Rock type description

The Sowerthwaite Formation comprises up to 300 m of siltstone and mudstone with interbedded volcaniclastic rocks, sandstone and conglomerates; the older Norber Formation is up to 160 m thick and consists mainly of calcareous siltstone and impure limestone (Aitkenhead et al., 2002; Millward and Stone, 2012).

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in the Pennines region and shows their surface extent on a map (Figure 14). 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 region described in this account encompasses parts of Yorkshire, Lancashire, Cheshire, Staffordshire, Derbyshire and Nottinghamshire. The Pennines form the dominant physiographical feature of the region, which extends from the Stainmore Gap in the north to the Midlands in the south.

The surface and subsurface structure of the Pennine region can be described in terms of three major structural events (orogenies) that affected the region and surrounding areas: the Caledonian, Variscan and Alpine orogenies (see Pharaoh and Haslam (2018) for a summary of the structural evolution of the British Isles). Distinct structural and sedimentary rock 'units' are associated with and separated by these events.

For the purposes of this report, the structures are described on the basis of their effects on three main rocks groups:

- Caledonian basement rocks — lower Palaeozoic strata and older
- older cover — Devonian to Carboniferous strata
- younger cover — Permian to Mesozoic (Triassic) strata

The oldest rocks of the region, Ordovician and Silurian strata, form the Caledonian basement and are seen at surface in the Craven inliers on the southern margin of the Askrigg block, where they occur in east-south-east-plunging folds that bring Ordovician rocks to outcrop in the west and the youngest Silurian rocks in the east. They are also proved at depth across the region in a number of boreholes. These rocks were deformed during the Early Devonian by the late Caledonian Acadian Orogeny, which resulted in the structure ('grain') of the Caledonian basement, a pronounced arcuate basement structural trend. This deformation trends north-eastwards in the west, veering east–west in the central part, turning to north-west in the east and reflecting the northward 'indentation' of the rigid Midlands microcraton crustal block into the more mobile rocks of the Caledonian fold belt. The basement structures were important in the development and location of many later Carboniferous extensional and compressional structures.

Ordovician and Silurian strata probably form the pre-Carboniferous basement throughout much of the region and represent the continuation of the Caledonide fold belt of northern England and the Lake District volcanic arc into the concealed Caledonides of eastern England. However, other than over the Askrigg block, pre-Carboniferous rocks are likely to be at depths greater than the depth range of interest. The rocks are strongly faulted, folded and cleaved. Because of its structural complexity and minimal surface outcrop, the nature of the Caledonian basement is poorly understood. Structure in the overlying Carboniferous and younger strata are better understood due to seismic reflection data acquired in the search for hydrocarbons which has provided detailed insights into the structure and evolution of the sedimentary cover succession.

Rocks of the Carboniferous Period (the older cover) were deposited during a major period of north–south, regional crustal extension, with a series of pulsed rift events that began in Late Devonian times with particularly active episodes during Courceyan, Chadian to early Arundian and mid to late Asbian times, although the magnitude and perhaps the timing of each pulse appears to have varied significantly from basin to basin. Major normal faulting occurred during the Carboniferous, producing a rifted topography and dividing the region into a system of rapidly subsiding, fault-controlled, tilted and structurally elevated fault blocks (highs) and intervening graben and half-graben (extensional basins). Stratigraphical sequences thicken markedly in the direction of tilt, commonly towards major basin-controlling faults. The large basin-controlling normal faults, which may have subsurface throws of several kilometres, generally display only quite small displacements at the surface, or may be entirely concealed beneath the post-rift succession. The surface expressions of the main Carboniferous fault structures therefore appear either as minor normal faults, or, quite commonly, linear zones of folding in the post-rift succession.

Faulting was followed by a long period of thermal relaxation and crustal sag (post-rift subsidence). By the latest Carboniferous times, basin subsidence in the region gave way to regional uplift due to Variscan crustal compression. During inversion, many of the major basin-bounding normal faults were partially reversed, or, more commonly, obliquely reversed. This resulted in a reduction in net normal displacements on the deep sections of synrift faults and produced local reverse faulting, anticlines and monoclines at higher stratigraphical levels with trends that reflect the underlying Palaeozoic basement structures.

By earliest Permian times, Variscan continental collision had led to final consolidation of the Pangaean supercontinent, with associated regional uplift. The younger cover succession that unconformably overlies Carboniferous rocks over parts of the region is tilted and locally faulted, but generally unfolded. This uppermost unit comprises about 40 per cent of the surface outcrop in the region, but less than 10 per cent by volume of the preserved sedimentary cover.

Strongly contrasting structural styles characterise the eastern and western parts of the region. To the east of the Pennine high, Permo-Triassic strata were deposited on the eastern England shelf, where subsidence was of a regional nature on the periphery of the basins of the Southern North Sea. To the west, the west Lancashire and Cheshire basins formed part of a major rift system that extended southwards to the English Channel and north-westwards into the East Irish Sea and Scottish waters. Development of these rift basins involved partial reactivation of the Carboniferous fault network but was mostly through the formation of a new, dominantly north–south-trending fault system, superimposed on the older fault network. This is consistent with east–west-directed extension reactivating basement faults in a different manner to that of the north–south, early Carboniferous extension.

The evolution of the region from the end-Triassic to the Quaternary is somewhat conjectural as almost no bedrock strata deposited in that period are preserved. Extensional basin subsidence probably continued through Jurassic and into Early Cretaceous times being largely controlled by the Permo-Triassic structural template. A period of post-rift, regional subsidence followed in the Late Cretaceous.

Cenozoic uplift probably comprised two distinct components: regional flexural uplift, possibly associated with development of the Scottish Tertiary igneous province, and, superimposed on this, more localised uplifts corresponding to basin inversions associated with Alpine crustal compression.

Cenozoic uplift is poorly understood but it is likely that features such as the Pendle Monocline and Pennine Anticline owe their origin more to Carboniferous and Mesozoic patterns of differential subsidence than the relatively recent effects of Cenozoic uplift.

5.3 MAJOR FAULTS

The major faults identified from UK3D modelling, published literature and maps of the region exhibit a variety of orientations and evolutionary histories, as a consequence of the complex structural history outlined above and described in Pharaoh and Haslam (2018). In the following descriptions, the major faults are described in terms of crustal 'domains'. Each domain contains a set of faults with a dominant orientation, usually reflecting the influence of structural control from the underlying basement and, frequently, a comparable displacement history, reflecting the behaviour of similarly orientated fault planes to extension or compression in the contemporaneous regional stress field.

It should be noted that the stated displacement values for faults derived from UK3D and described in this account are for specific locations or levels and are not characteristic of the whole fault along its length, or indeed its depth. Many faults are long lived, with evidence of repeated reactivation and movement. As such, extensional (normal) displacements tend to be greater at depth, decreasing in the shallower subsurface.

The pre-Permian rock framework of northern England and Wales is divided by lineaments and faults into a series of major terranes (Pharaoh and Haslam, 2018). Beneath the Pennines region, three main basement trends are evident, reflecting a long-known understanding of a Midlands microcraton 'indentor' with the strong north-east Caledonian trend in Wales being traced in an arc around the apex of the indentor into the north-west-trending, concealed East Midlands Caledonides (Turner, 1949; Pharaoh el al., 1987; Fraser and Gawthorpe, 1990; 2003). This outer arc continues northwards as far as the Iapetus suture, which separates the Welsh and East Midlands Caledonides from the Laurentian Caledonides of Scotland and the northern part of Ireland. The northern limit of the East Midlands Caledonides is marked by the north-west-trending Morley–Campsall line (the 'south Humberside–Hewitt lineament' of Fraser and Gawthorpe, 2003). This links with the Malvern line, which is also recognised as a major lineament running north–south through the apex of the microcraton and continuing to the north within the Caledonides, following the Red Rock and Pennine–Dent fault zones.

In the west and south-west of the region, faulting has a more northerly to north-westerly trend, more akin to the East Midlands Caledonide basement trend. This area lies to the north of the enigmatic and poorly constrained, north-east-trending Bala–Llanelidan lineament. Fault orientations to the north of this lineament may reflect the presence and influence of East Midlands Caledonide basement trends. These domains naturally divide the region into a number of structurally distinct areas, generally fault-bounded and that correspond to younger structural highs and sedimentary basins. Thus the main structures have been controlled in both extension and compression by the underlying basement features.

The surface and subsurface structure of the region can furthermore be described in terms of three major rock units, separated by unconformities, whose degree of structural deformation increases with depth and age (Aitkenhead and Wray, 2002). The oldest and deepest unit comprises the Caledonian basement, which crops out in the Craven inliers, the rocks of which are strongly faulted, folded and cleaved. The upper two units form the sedimentary cover sequence which rests with strong unconformity upon the basement. A Carboniferous succession, present virtually everywhere within the region, comprises variably thick, tilted, faulted and locally folded, extensional-basin strata. It constitutes more than 60 per cent of the surface outcrop in the region, and, by volume, more than 90 per cent of the preserved sedimentary cover.

In parts of the region, Carboniferous rocks are overlain unconformably by Permo-Triassic strata, which are tilted and locally faulted, but generally unfolded. This uppermost unit comprises about 40 per cent of the surface outcrop in the region, but less than 10 per cent by volume of the preserved sedimentary cover.

For the current region, the main faults are best described in terms of two main stratigraphical groups or outcrop areas (Figure 13):

- Structures of the younger cover (Permo-Triassic outcrop) — post-Carboniferous rocks of Permo-Triassic age occupy the low ground on both sides of the Pennine high, described here as:
    - eastern England
    - western area, including the intervening the south Lancashire coalfields areas — faulting affecting the Permo-Triassic strata extends into the older cover rocks of the coalfield area and so these are described together
- Structures of the older cover (Carboniferous and older rocks) — predominantly affecting pre-Permian strata

Many of the north-north-west-trending structures affecting the younger cover rocks have the same trends as those seen affecting, and which are pervasive across, the outcrop of the older cover rocks, particularly over ancient structural highs, such as the Rossendale area, where deposition of younger cover strata may have been attenuated or absent. Due to the absence of younger cover rocks, it is not possible to state which structures affecting older cover would have also affected the younger cover sequences, so they are described separately.

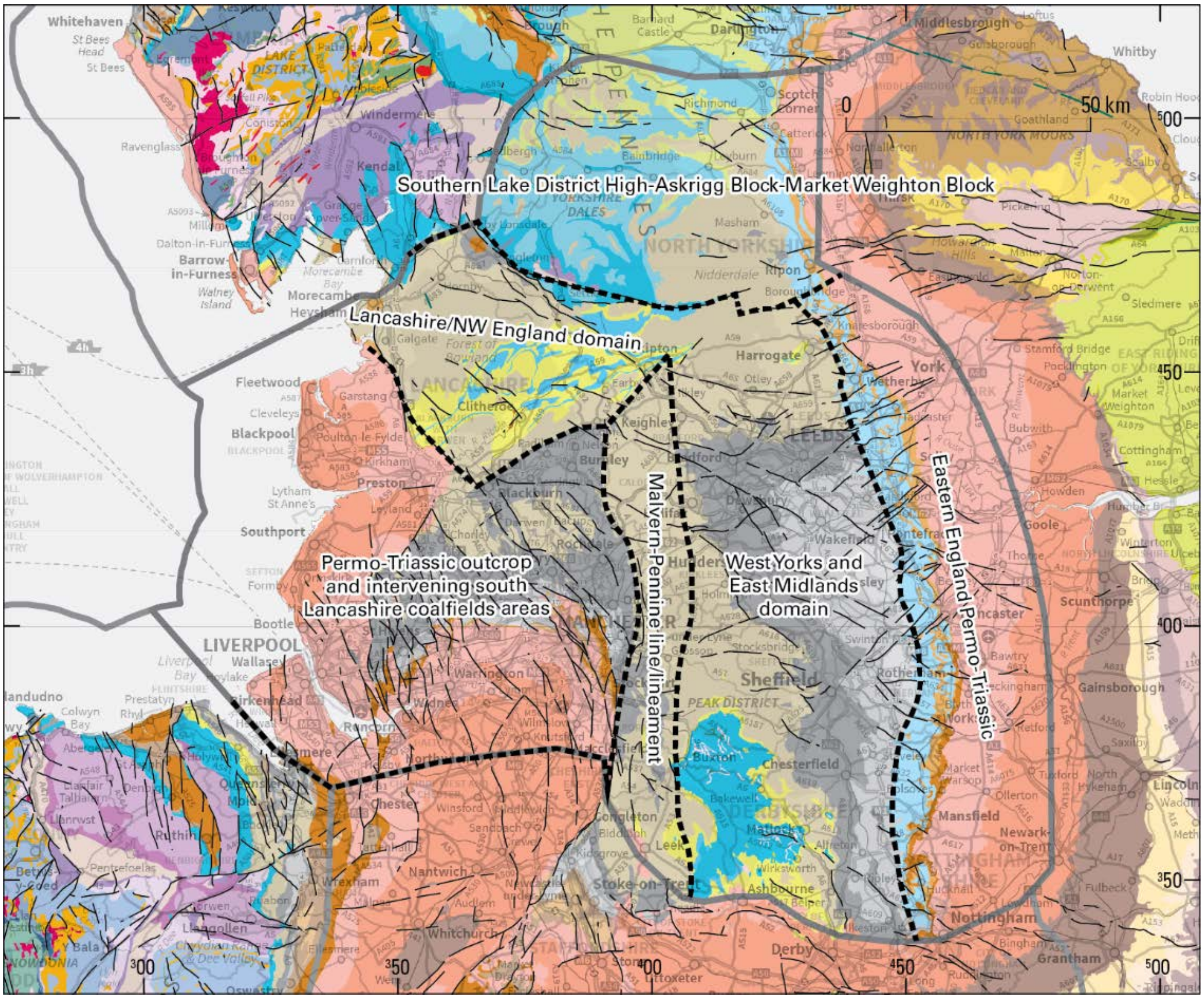


Figure 13 The areas described in this section. Geology based on the published 1:625 000 scale map of the UK. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey digital data © UKRI 2018

Within these two broad subdivisions, structures fall into further subregions (structural domains), based largely upon the effects that Palaeozoic basement structures had on subsequent extensional and compressional cycles (Figure 13). These subregions are introduced and defined below in the relevant sections.

Seismic reflection data coverage varies in both the density and quality of data, in part related to the vintage of differing surveys. The younger cover (Permo-Triassic outcrop) has the best density of coverage, whilst the basement massifs to the north of the region have no coverage due to their lack of hydrocarbon prospectivity. Areas of Tournaisian–Visean shelf carbonates that developed over old structural highs, like the Derbyshire dome in the south of the region, have little prospectivity and no seismic reflection coverage. Elsewhere, those areas of older cover reflecting the development of major Tournaisian–Visean basins and thicker, basinal strata have reasonable coverage. Areas of younger older-cover rocks (Namurian–Westphalian strata) have generally poor coverage, except where underlain by thicker Tournaisian–Visean basin successions east of the Pennines.

5.3.1 Structures of the eastern younger cover (Permo-Triassic outcrop) — eastern England

To the east of the Malvern–Pennine line (or high), subsidence during Permo-Triassic times was mainly of a flexural nature with only minor faulting. Permo-Triassic rocks thicken and dip gently eastwards away from the Pennine high across the eastern England shelf, towards the offshore basins beneath the Southern North

Sea. The eastern Permo-Triassic crop is structurally simple with only minor faulting along predominantly north-east lines, the vast majority of which show less than 200 m displacement. There are some exceptions, notably the north-west-trending Morley Campsall–Askern–Spital structure, which is a long-lived lineament traversing the majority of the current region and extending south-eastwards into the adjacent Eastern England region (Figure 14). The fault is described in more detail in the description of Carboniferous and Permian strata in the West Yorkshire and East Midlands domain.

5.3.2 Structures of the younger cover (Permo-Triassic outcrop) and intervening older cover of the south Lancashire coalfield areas

The Permo-Triassic Cheshire basin area, the coastal belt of Lancashire from the Wirral up to the Fylde, and the Lancashire coalfield area all lie in the western half of the region. Throughout most of the region the structures trend north-north-west except in the south where the structures trend north-east and are aligned with the Welsh Borderland fault system of the Central England, Welsh Borderlands and Wales regions (e.g. Woodcock and Gibbons, 1988). The Welsh Borderland fault system formed the boundary between the Midlands microcraton and the Welsh basin throughout the early Palaeozoic.

The Permo-Triassic crop from the Wirral northwards to the Fylde forms the eastern margin of a major Permian to Mesozoic extensional basin complex offshore in the East Irish Sea (the East Irish Sea basin; Jackson and Mulholland, 1993; Jackson et al., 1995). Throughout Permian to Early Jurassic times, subsidence in the East Irish Sea basin occurred in a series of depositional pulses, linked to lithospheric extension, and broadly related to the opening of the Atlantic to the west, separated by non-sequences at major lithostratigraphical boundaries.

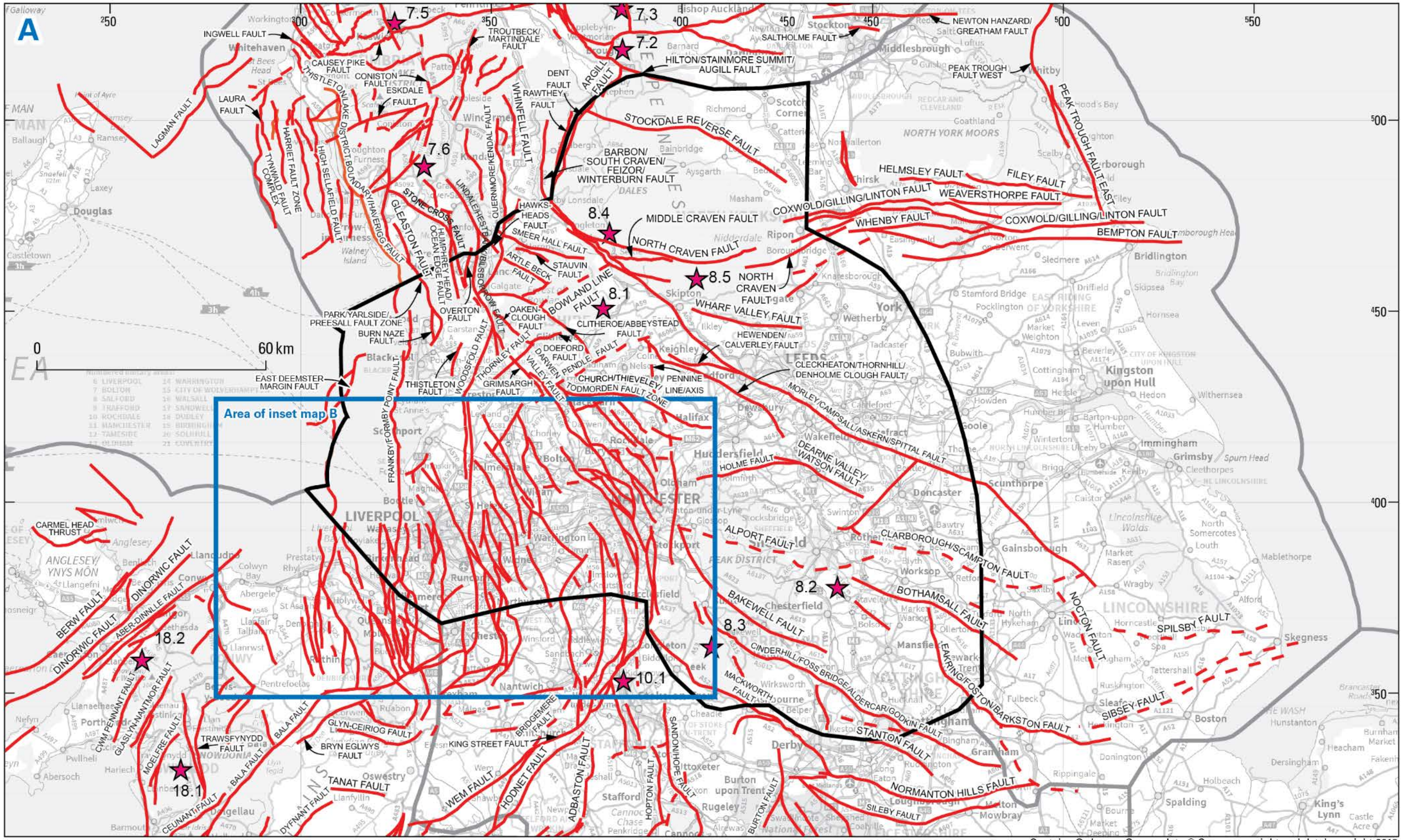
Fault trends in the Permo-Triassic Cheshire basin and Lancashire coastal area reveal two populations (Chadwick and Evans, 1995; Chadwick, 1997). In the south, faults striking predominantly north-east (Caledonian trend) indicate a strong degree of basement control, particularly at the faulted south-east margin. Farther north, faults with north–south strikes constitute the majority of faults within the basin. They are interpreted to have formed perpendicular to the initial basin-forming extension (roughly east–west), and are suggestive of a much weaker basement influence. Fault displacement analysis (Chadwick, 1997) also reveals a north–south split, with two distinct fault populations. In the south, extension was concentrated on the large, dominantly oblique-slip, basin-margin faults. To the north, however, extension was distributed on numerous small to medium-sized, dip-slip faults. Again, the two fault populations are attributed to a variable degree of basement control: major reactivated Caledonian basement structures controlled basin faulting in the southern part of the basin, whereas farther north the basin faults developed more or less independently of a less faulted, more isotropic basement.

The Cheshire basin area is affected by groups of faults with similar orientation and almost exclusively normal displacement. These are best described in terms of the following major fault groups:

- Wem–Hodnet–Bridgemere–Red Rock fault zone
- North Cheshire basin fault belt
- North-west Cheshire basin, Lancashire coastal plain to the Fylde and south Lancashire coalfield fault belt

Each group contains a number of faults with a comparable orientation and structural history, reflecting the analogous behaviour of similarly orientated fault planes to extension or compression in the contemporaneous regional stress field. Where evidence for the siting and character of these structures is known, it is described in brief. Within the Permo-Triassic crop, other important faults are present, distant to these main groups of faults, and are described separately where appropriate

Extending from the Central England region northwards into the current region is the complex, braided, generally south-west to north-east-trending, Wem–Hodnet–Bridgemere–Red Rock fault system that extends over 100 km across central England (Evans et al., 1993; Chadwick and Evans, 2005; Smith et al., 2005). This fault zone comprises a series of *en échelon* faults and extends into the current region as the subset Wem–Red Rock fault zone, which has moderate westerly dips (45° to 60°) and a normal displacement of around 460 m, affecting Permo-Triassic strata.



Areas of folding

Major faults transecting depth of interest

Major fault terminating in depth of interest

Pennines and adjoining areas

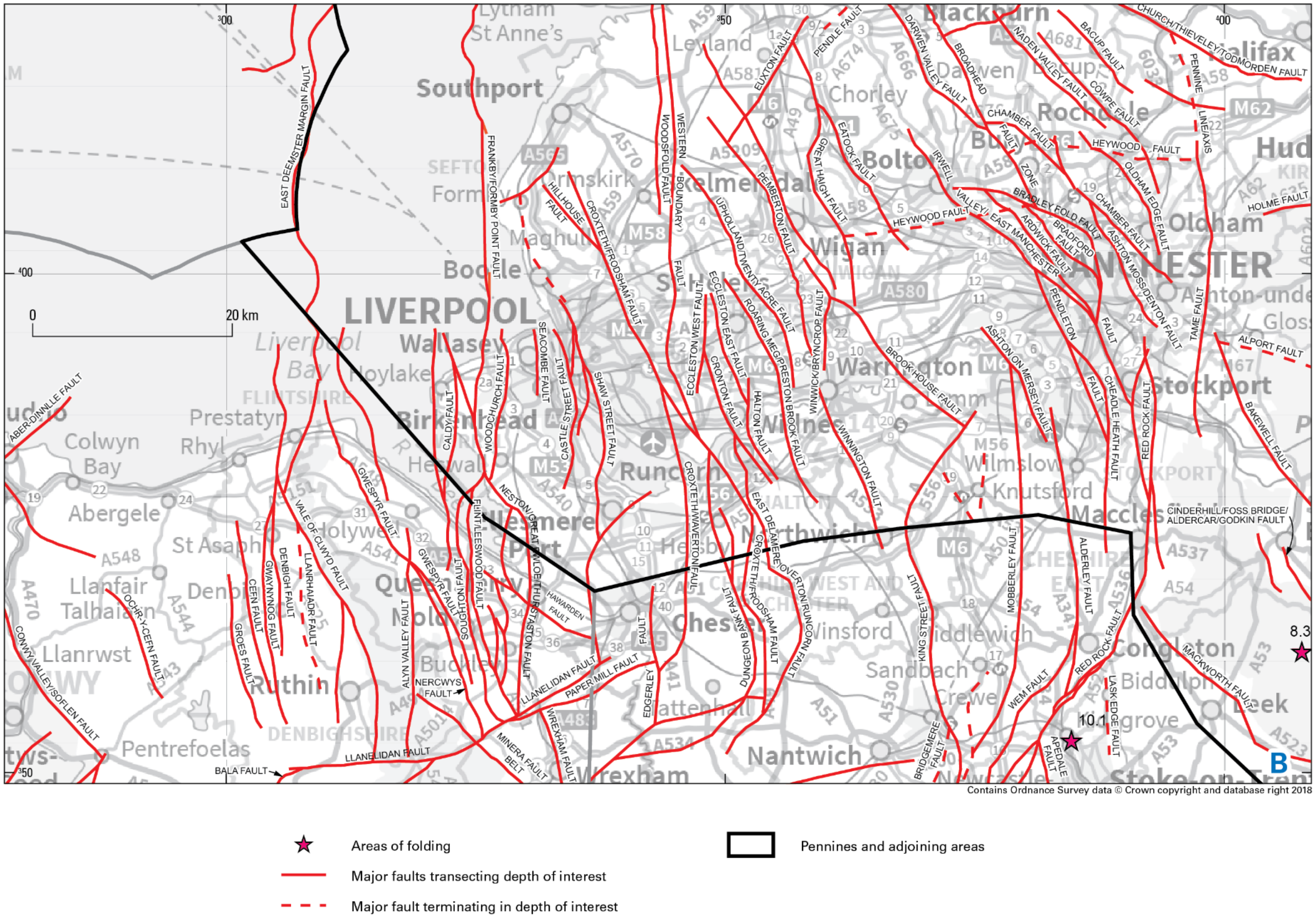


Figure 14 A: Major faults and areas of folding in the Pennines region. B: Inset map. Area of inset map shown on A. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

The Wem, Bridgemere and Red Rock faults were the most important syndepositional, basin-controlling faults controlling the eastern edge of the Cheshire basin (Hains and Horton, 1969). They comprise a series of large, north-east-trending, down-to-west, normal faults with a combined westward downthrow exceeding 4000 m at the base Permo-Triassic level (Chadwick and Evans, 2005). The fault zone lies along a major lineament in the early Palaeozoic basement, reactivated from Mid Ordovician and possibly Proterozoic times onwards (Smith et al., 2005). Linked to this and probably controlling its development is a north-west-dipping Hercynian thrust (or thrusts), which was reactivated in extension during Permian and Mesozoic times and controlled normal faulting and basin formation (Evans et al., 1993; Chadwick and Evans, 1995; 2005). To the south, the Wem–Red Rock fault zone has a normal throw exceeding 2500 m at the base Permo-Triassic level (Evans et al., 1993; Chadwick, 1997). The combined downthrow gradually decreases northwards along the system to a few hundred metres or less in the north (Evans et al., 1993; Chadwick, 1997).

To the west, within the hanging-wall block of the Wem–Red Rock fault zone (i.e. the Cheshire basin), a series of smaller, northerly trending faults extend northwards into the region from the Central England region to the south. Two of these are the down-to-east Brook House–King Street and Mobberley faults. The main down-to-west fault is the Alderley Fault, cutting across the Cheshire basin for some 30 km, with a normal throw of about 800 m in Triassic strata, decreasing northwards.

The Mobberley Fault is parallel to and west of the Alderley Fault and extends some 30 km across the Cheshire basin, merging with the Ashton Moss Fault in the north. It has a normal displacement of over 1750 m in UK3D.

The Brook House–King Street Fault is a complex, sinuous, down-to-east structure, comprising a number of segments across which preserved strata thicken eastwards, notably the Permian sequence. This indicates that the fault was an important feature early in basin evolution and constitutes the major structure in the northern part of the Cheshire basin. The King Street segment is up to 48 km in length and links to the Brook House Fault via subvertical, possibly transfer, faults. The fault is typically planar and quite steeply dipping (70˚), but in parts is less steep, with a somewhat listric geometry developed. Normal throws on the King Street Fault approach 1000 m at the base of the Permo-Triassic sequence, but diminish north and south. The Brook House segment is a north-west-trending, down-to-north-east, normal fault and about 15 km long. The throw on the fault locally exceeds 1000 m, decreasing upwards and also northwards.

To the north, the Wem–Red Rock fault zone gives way to the north Cheshire basin fault belt, which herein comprises a north-west-trending plexus of arcuate, down-to-east fault structures that define the northern and north-eastern margin of the Cheshire basin and the south-eastern edge of the exposed Lancashire coalfield, where it affects the older cover. For the purpose of this account it includes the Darwen Valley, Broadhead, Irwell Valley–East Manchester, Pendleton, Cheadle Heath, Ardwick, Bradford, Chamber, Ashton Moss–Denton, Heywood, Oldham Edge, Naden Valley, Cowpe and Bacup faults (Wright et al., 1927; Tonks et al., 1931). The majority of the structures are normal faults, between which numerous smaller faults, including those with a north-east trend, are present, their orientations being suggestive of Riedel shear sets. These, together with variations in displacement direction along some of the faults, are perhaps indicative of an element of lateral displacement on the major named faults.

The most westerly fault of this group is the Darwen Valley Fault, forming the western margin of the Darwen coalfield. It is mapped over 26 km as normal fault downthrown to the north-east, with greater than 200 m displacement, but is not currently accurately modelled in UK3D. The north-west-trending Irwell Valley–East Manchester–Pendleton–Cheadle Heath fault zone, with a downthrow to the east, is an arcuate fault plexus. The Irwell Valley–East Manchester segment is mapped over about 36 km and has a displacement of almost 830 m in UK3D. To the south-east, the Pendleton Fault splays off south, running more north-north-west for about 19 km, with down-to-east normal displacement not currently accurately represented in UK3D. It overlaps with the north–south-trending Cheadle Heath Fault mapped to the east, which runs mostly parallel, and with opposing downthrow direction, to the northern end of the major down-to-west Red Rock Fault. The Cheadle Heath Fault has a length of approximately 22.5 km and a displacement of about 290 m of the younger cover in UK3D.

The arcuate Bradford and Bradley fold–fault pair are opposing in displacements, producing a north-west to south-east trending, lozenge-shaped graben in which Permo-Triassic strata are preserved. They both have more than 200 m of normal displacement. The Chamber–Ashton Moss–Denton fault zone is over 26 km in length, with a general down-to-east normal displacement of more than 200 m, but has in places down-to-west sections. It is not currently represented accurately in UK3D.

The Oldham Edge Fault is the most easterly fault in this group, mapped over more than 15 km and with over 930 m displacement in UK3D. The fault is complex and not well constrained, showing varying downthrow directions along its length.

The northern extent of the north Cheshire basin fault belt is roughly marked by the sinuous Church–Thievely–Todmorden fault zone: an east–west-trending, complex, braided, *en échelon* series of faults, extending over 44 km and with up to 1290 m displacement along their length in UK3D. However, given the various fault segments, the downthrow direction and amount is variable.

The north-west Cheshire basin, Lancashire coastal plain and south Lancashire coalfield fault belt comprises a plexus of generally north-north-west and north-trending, often arcuate fault structures that define the north-western and western margins of the Cheshire basin, and, in many places, the eastern boundary of the Permo-Triassic outcrop and the south-western edge of the exposed south Lancashire coalfield, across which they are mapped. For the purpose of this account it includes the Pemberton-Winnington, Upholland–Twenty Acre, Roaring Meg–Preston Brook, Eccleston East–Halton, Cronton, Eccleston West, Western Boundary and East Delamere–Overton–Runcorn faults (Wright et al., 1927; Tonks et al., 1931; Jones et al., 1938). Again, they lie to the north of the proposed north-east-trending Bala–Llanelidan lineament. Their orientation suggests a weaker basement fabric, with basin faults developing somewhat independently of a less faulted, more isotropic basement during later crustal extension (Chadwick, 1997). Numerous smaller faults, including those with a north-east to south-west trend are present and their orientations are suggestive of Riedel shear. These, together with variations in displacement direction along some of the faults, are perhaps indicative of an element of lateral displacement on the major named faults.

The main faults affecting the Permo-Triassic strata across the Wirral and the Lancashire coastal belt include the Croxteth–Frodsham–Waverton fault zone; the Dungeon Banks, Shaw Street, Caldy, Frankby–Formby Point, Woodchurch, Seacombe, Hillhouse, Western Boundary, Euxton, Woodsfold, Grimsargh, Thistleton, Ocean Edge and Overton faults, and the Park–Yarlside–Gleaston–Preesall and Lindale–Hest Bank–Bilsborrow fault zones that extend northwards into the adjacent Northern England region. This group of faults affecting the Permo-Triassic crop have more northerly trends and generally down-to-west, normal displacements, being related to the extension that produced the important offshore Permo-Triassic depocentre of the East Irish Sea. This is crossed by numerous broadly north–south-trending faults including the East Deemster Margin Fault, which forms the western limit of the east Deemster basin (Yaliz, 1997) located offshore of the Fylde to the west of the Formby Point Fault, which marks the western limit to the Formby Point platform.

The Croxteth–Frodsham–Waverton fault zone is a complex, braided structure, extending into the south-west of the region from the adjacent Central England region. It comprises two main segments: the Croxteth–Frodsham and the Croxteth–Waverton faults, which coalesce south-east of Liverpool and extend north-westwards across the region as one fault mapped over a distance of 42 km, with a westward normal downthrow exceeding 840 m in UK3D. In UK3D, the Western Boundary and Croxteth–Frodsham faults are shown as interacting in a plexus of faults to the south-east of Liverpool. In this area, the Croxteth–Frodsham Fault is shown as extending south-eastwards into the Central England region as a down-to-east, sinuous fault (south of the junction with the Croxteth–Waverton Fault) and the relationships are not clear.

Within the region and to the east of the Croxteth–Waverton Fault is the Dungeon Banks Fault, a north–south-trending, down-to-east normal fault, with more than 200 m displacement. Together, the two faults define a north–south-trending horst.

A series of north–south faults cross the Wirral, including the Shaw Street, Caldy, Frankby–Formby Point, Woodchurch and Seacombe faults. These variously extend offshore into the Liverpool Bay, River Mersey and Dee estuary–North Wales areas. The most significant is the Frankby–Formby Point Fault, extending as a series of *en échelon* faults some 75 km from The Wirral northwards and just offshore to near Fleetwood, with up to 960 m normal displacement in UK3D.

The Woodchurch Fault, which has a length of over 15.5 km and a displacement of almost 890 m in UK3D, is a down-to-west, normal fault defining the eastern margin of a north–south horst structure, the western margin of which is formed by the Frankby–Formby Point Fault.

North of The Wirral in the Lancashire coastal plain area, faulting is generally north-north-west trending, but ranging from north-west to north-east, with faults extending into the adjacent Northern England region. They include the Western Boundary, Euxton, Woodsfold, Thistleton, Grimsargh, Overton and Ocean Edge faults, and the Park–Yarlside–Gleaston–Preesall and Lindale–Hest Bank–Bilsborrow fault zones.

The Park–Yarlside–Gleaston–Preesall fault zone is a complex, braided, northerly and north-westerly trending, arcuate, down-to-west, normal fault zone. It extends north across Morecambe Bay into northern England, where it lies to the east of the Lake District boundary fault zone and is joined by a more north-north-westerly trending splay, the Gleaston Fault. The Preesall Fault is the arcuate segment extending into and across the region, becoming more south-west to north-east-oriented southwards. It is a down-to-west, normal fault with a length of about 22 km and displacement of around 970 m in UK3D, and defines the eastern boundary of the Preesall salt field onshore to the east of Blackpool and Fleetwood. The Burn Naze Fault has been identified from seismic reflection data as a down-to-east structure antithetic to the Preesall Fault. It runs along the Wyre estuary for part of its length and has more than 200 m of normal displacement, but is not currently shown in UK3D.

The Lindale–Hest Bank–Bilsborrow–Grimsargh fault zone is a complex, braided, north-north-westerly trending, *en échelon* series of down-to-west, normal faults (Jackson et al., 1995; Akhurst et al., 1997) that is not accurately represented in UK3D. The mildly sinuous Bilsborrow Fault is the segment extending into and across the region, the line of which is not precisely defined but which in parts forms the boundary between the Permo-Triassic and Carboniferous outcrops. The fault is approximately 30 km in length and downthrows to the west, with up to 430 m of normal 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 somewhat conjectural owing to the thick cover of superficial deposits and the 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.

The Woodsfold Fault is an important down-to-west, basin-bounding, syndepositional, normal fault within the Permo-Triassic outcrop. It splays south-westwards from the Bilsborrow Fault to around Freckleton on the River Ribble, south of which it trends north–south and is *en échelon* to the Western Boundary Fault in the south. It has a length of over 42 km and a displacement that exceeds 200 m, but it is not well represented in UK3D.

To the west, a complex series of generally non-planar faults is developed, displaying easterly hade and downthrow directions antithetic to the Woodsfold Fault. The faults diverge upwards, and the most westerly is known as the Thistleton Fault. Together, the two faults define the Kirkham basin, which is regarded as a Permo-Triassic depocentre. Indeed, the centre of the basin, rather than being synclinal in form, is marked by the presence of a broad, anticlinal structure named the Elswick dome (Aitkenhead et al., 1992). The Western Boundary Fault (also known as the Lancashire Coalfield Boundary Fault (Jackson et al., 1995)) is a north–south-trending, down-to-west, normal fault, the precise position and course of which is poorly constrained. It forms the boundary to the Permo-Triassic and Carboniferous outcrop over its southern half, but northwards appears to run *en échelon* to the Woodsfold Fault, the main basin-bounding fault stepping eastwards, and the north-east-trending Euxton Fault (Price, 1963). The fault is over 40 km in length and has up to 350 m displacement in UK3D.

5.3.3 Structures of the older cover (Carboniferous) and earlier rocks

The pre-Permian outcrop constitutes more than 60 per cent of the surface outcrop in the current region, of which the vast bulk is of Carboniferous age (older cover). These strata were laid down during a number of crustal extension phases that formed a series of fault-bounded, tilted blocks. These produced a network of structural lows (sedimentary basins) and intervening structural highs, over which sedimentation was reduced or absent. The faults were largely controlled by basement structures, mainly reflecting Caledonide trends and lineaments. These factors led to a number of structural provinces or domains, defined by major fault zones, within which the nature and trends of structures are similar. The faulting affecting the pre-Permian outcrop is thus described in terms of the following Tournaisian–Visean synrift structural domains or elements:

- southern Lake District high–Askrigg block–Market Weighton block — major basement massifs, forming a northern ‘arc’ to the area and over which older cover strata are much thinned or absent
- Malvern–Pennine–Dent lineament — the ‘Pennine line’ (or high), a prominent north–south lineament extending to the southern margin of the Craven basin and affecting mostly Namurian strata at crop, but forming the divide between two distinct domains underlain by basement of differing type

- Lancashire–north-west England domain — areas to the west of the Malvern–Pennine–Dent lineament, including the Bowland, Craven and Widnes basins, and the Bowland and Rossendale–central Lancashire highs
- West Yorkshire and East Midlands domain — areas to the east of the Malvern–Pennine–Dent lineament, including the main Carboniferous depocentres, namely the Goyt and Gainsborough troughs, the Widmerpool gulf, the Leeds–Harrogate, Huddersfield and Alport–Edale basins, the Pennine high, and the Derbyshire platform–East Midlands shelf

Each of these structural domains is defined by large, long-lived fault zones that originated from, and were controlled by, the underlying Caledonian basement fabric and contained structures. These have been reactivated in both extension and compression on a number of occasions. They are commonly deeper than the depth range of interest, but are nevertheless important structures that controlled the development and distribution of rock types and subsequent folding of the overlying, younger parts of the older cover succession.

Seismic coverage generally varies from good (over the main Tournaisian–Namurian depocentres) to poor (over the basement massifs and coalfields).

The northern areas of the region are underlain by major, fault-bounded basement massifs: the southern Lake District high and the Askrigg and Market Weighton blocks. The Askrigg block, underpinned by the rigid Wensleydale granite, is the principal structural high in the region, forming a northerly dipping tilt block bounded to the south by the Craven faults, to the west by the Dent Fault and to the north by the largely concealed Stockdale Fault. Caledonian basement lies at depths generally less than about 1500 m below OD and locally comes to crop, for example in the folded Caledonian basement rocks of the Ingleton and Horton inliers. Carboniferous rocks on the Askrigg block are virtually undeformed, dipping only gently northwards, and are thin or incomplete, indicating that the block remained emergent through much of the Carboniferous.

Close to the northern limit of the region, the Stockdale Fault forms, at the surface, a roughly east-trending system of minor normal and reverse faults and folds, with an overall northerly downthrow, referred to as the 'Stockdale disturbance' (Dunham and Wilson, 1985; Kirby et al., 2000). It has a length of over 57 km and displacement of almost 250 m in UK3D, but the nature of the structure at depth is poorly understood. It has been proposed as marking the northern margin of the Askrigg block on the basis of gravity data (Bott, 1967), and is almost certainly faulted with large normal down-to-north displacements at base Carboniferous levels estimated at between 1000 and 3000 m (Collier, 1991; Chadwick et al., 1996).

The southern margin of the Askrigg block is stepped and formed by a complex, braided, *en échelon* series of north-west and east–west-trending, down-to-south or south-west faults, collectively referred to here as the Craven fault zone. The North and Middle Craven faults are the two main northern fault zones, with many associated minor faults. The North Craven Fault is the main northern fault, with arcuate geometry, and taken up eastwards on a southerly *en échelon* fault around Pateley Bridge to define the southern edge of the Askrigg block thereabouts. Collectively the two are referred to as the North Craven Fault, which has up to 1180 m normal displacement in UK3D and extends over 70 km eastwards into the adjacent eastern England region as the North Craven–Vale of Pickering–Flamborough Head fault zone. The latter is a sinuous, braided complex of *en échelon* faults with a west–east trend and a total mapped length exceeding 175 km that extends to the Dowsing–South Hewett fault zone of the Southern North Sea basin (Chadwick and Evans, 2005).

The Middle Craven Fault is a shorter (about 16.5 km in length), more east–west-trending fault, with a steep to moderate (locally as little as 45˚) southerly dip. Displacement exceeds 200 m and locally is greater than 500 m at base Tournaisian levels. The South Craven–Feizor–Winterburn fault zone is a complex, arcuate fault system trending north-westwards in the region, but turning north–south into the adjacent Northern England region as the Dent fault zone. Defining the southern margin of the Askrigg block and the northern margin of the Ingleton coalfield, it is *en échelon* with the north-western end of the north-west-trending Morley–Campsall–Askern–Spital fault zone, which continues south-eastwards across the region into the adjacent Eastern England region and forms the boundary between the Askern–Spital high and Gainsborough trough in the West Yorkshire and East Midlands domain.

The Dent fault zone marks the western margin of the Askrigg block, running north-east along the boundary of the region. It is a complex, braided series of anastomosing, vertical to steeply west-dipping fault strands, together representing a major oblique-slip fault zone (Underhill et al., 1998; Aitkenhead and Wray, 2002). 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 structure at the surface comprises an east-facing and slightly overturned monocline, which is dissected by the fault strands along the length of the fault system. The fault zone has a length of at least 31 km, although the amount of reverse displacement is uncertain, but may well exceed 1000 m. The fault system represents an early Palaeozoic lineament, reactivated during the 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 and Wray, 2002). Younger movements may also have occurred but are difficult to document and are not thought to be significant.

The southern Lake District high, essentially the south-dipping flank of the Lake District block, lies mostly to the north-west of the region, but its southern margin underlies the north-western areas, where it deepens gradually southwards and is cut by a series of north–south faults marking small sub-basins. The main fault of this type is the down-to-west Quernmore–Kendal Fault, which in UK3D is mapped over 49 km across the current and adjacent Northern England regions, with a normal displacement of over 350 m. It is not well imaged on seismic reflection data, but 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–south-trending gravity gradient and its origin is still somewhat problematic, with both normal (down-to-west) and reverse (down-to-east) net displacements possible.

The north-trending Pennine line or axis is a prominent linear feature, stretching nearly 100 km southwards from the southern margin of the Craven basin, with a number of faults and folds affecting mostly older cover (Namurian) strata at outcrop (Wright et al., 1927; Evans et al., 2002; Aitkenhead and Wray, 2002). Generally thought to be linked with the Dent fault zone to the north, it is a complex and poorly understood structure separating the more north-west-trending, eastern England Caledonide basement to the east from the north-east-trending Caledonides to the west. The overall structure is generally asymmetrical, with steep dips on its western flanks and gentle dips on its eastern flanks. It is thought to be underlain by basement-involved and Carboniferous faults that accommodated movements on the various, mostly concealed, syndepositional faults defining the mosaic of early Carboniferous blocks and basins. Fundamental fault zones linked with and showing this trend include the Tame and Red Rock faults in the south of the region and, farther south, the Lask Edge–Sandon–Hope Fault (Lee, 1988). In the north, the structure comprises a west-facing monocline underlain by an east-dipping fault showing net reverse (down-to-west) displacement of the Caledonian basement (Evans et al., 2002). Southwards, the structure takes on a more anticlinal form, swinging into a north-westerly orientation near Todmorden, where it is associated with a complex series of faults known as the Todmorden smash belt. Further south still, the structure is less well defined for several kilometres, before appearing again as the Mossley Anticline, a generally asymmetrical, west-verging structure. Towards the southern edge of the region, it branches into a series of *en échelon*, north-trending folds, some of which are well seen at outcrop. South of this, the lineament appears to extend into, and across, the Central England region as the Sandon–Hope Fault.

The Lancashire–north-west England domain comprises a number of important, fault-bounded, Tournaisian–Visean extensional basins and intervening highs, controlled by north-east to south-west-trending faulting. The majority of the faults are concealed, with likely kilometre-scale displacements at basement levels below the depth range of interest. However, all significantly affect the distribution of strata and rock types, and some suffered reactivation and reversal of movement during the Variscan Orogeny to create important inversion anticline structures in the older cover rocks. An important fault of this type is the north-east to south-west-trending, northerly dipping, down-to-north Pendle Fault, separating the Craven basin from the central Lancashire high to the south and associated with the largest Variscan fold in the region, the Pendle Monocline (see folding section). Down-to-north, normal displacement on this fault all but dies out in the Namurian, but could still be present at around 1000 m depth, but the main disturbance associated with fault reversal is this southerly verging Pendle Monocline, located above the fault.

Antithetic to the Pendle Fault is the similarly trending, down-to-south-east Bowland Line–Doeford–Whitwell–Thornley fault zone, extending some 36 km. The structures, offset by the north-west Clitheroe–Abbeysteads fault zone, define the northern boundary of the main Craven basin depocentre and the south-eastern margin of north-westerly dipping tilt blocks forming the Lancaster Fells–Bowland high and South Fells tilt blocks. The southern margin faults affect strata at less than 1000 m depth and have variously suffered reversal, in particular the Doeford Fault, which displays up to 1000 m normal displacement at Tournaisian levels (3–4 km depth) but has reverse displacement at shallower levels (Kirby et al., 2000).

The Clitheroe–Abbeysteads fault zone, mapped over a distance of about 36 km with a displacement up to 1530 m in UK3D, is one of a number of similarly trending faults in this area, including the smaller Oakenclough (approximately 13 km in length), Artlebeck (approximately 13 km in length), Stauvin (approximately 9.5 km in length) and Smeer Hill (approximately 25 km in length) faults, all of which have displacements greater than 200 m. The fault zone has a long history of movement; its orientation and the fact the Bowland Line–Doeford–Whitwell–Thornley faults all stop against it suggest it may have acted as a transfer fault during the Tournaisian–Visean, perhaps also having an element of oblique or transcurrent motion in subsequent compressional phases.

The West Yorkshire and East Midlands domain comprises a number of important, fault-bounded, Tournaisian–Visean basins and intervening highs, controlled by north-west to south-east-trending faulting inherited from Caledonian basement trends. The majority of the faults are concealed, with often kilometre-scale normal displacements at basement levels found below the 1000 m depth limit. However, all significantly affected the distribution of strata and rock types, and some suffered degrees of reactivation and reversal of movement during the Variscan Orogeny, though to lesser degrees than those to the west of the Pennine line.

Important faults of this type are all 29 km or longer and with greater than 200 m displacement, and extend into the adjacent Eastern and Central England regions. They include:

- the regionally important Morley–Campsall–Askern–Spital fault zone, extending eastwards into the Eastern England region and the Wharf valley (29 km; 228 m displacement)
- the Holme–Dearne Valley–Watson (>45 km; 250–650 m displacement), Alport (approximately 55 km; >3.3 km displacement) and Bakewell (54 km; 1990 m displacement) faults, lying within the region
- the Clarborough–Scampton (approximately 66 km; >490 m displacement), Bothamsall (49 km, approximately 360 m displacement) and Eakring–Foston–Barkston (approximately 69 km, 1765 m displacement) fault zones in the east of the region, extending eastwards into the adjacent Eastern England region
- the Mackworth (approximately 44 km, 400 m displacement) and Stanton (approximately 29 km, 325 m displacement) faults
- the Cinderhill–Foss Bridge–Aldercar–Godkin (approximately 92 km, 805 m displacement) fault zone to the south, which extends southwards into the Central England region

As previously introduced, the Morley–Campsall–Askern–Spital fault zone is an important, 151 km-long, north-west-trending lineament traversing much of the region, affecting Carboniferous and Permo-Triassic strata on the eastern margins and extending into the adjacent Eastern England region. The down-to-south fault zone passes north-westwards into the South Craven fault zone, but is a poorly understood structure separating the Tournaisian–Visean Leeds–Harrogate basin from the Huddersfield basin to the south. Hereabouts, displacements are 200 m or less at Visean levels with lesser displacements in the Namurian–Stephanian cover. Traced south-eastwards, it becomes a demonstrably larger structure, forming the northern margin of the Gainsborough trough and separating it from the Askern–Spital high to the north. In the Westphalian and Permo-Triassic strata it is mapped as a braided series of faults (shown in Figure 14 as the generalised Morley–Campsall–Askern–Spital fault zone), including the Stainworth, Askern and Hatfield–Woodhouse faults, all down-to-south normal structures (Gaunt and Goodwin, 1994). These faults are associated with minor opposing faults that form a series of graben along the structural culminations in these parts.

5.4 FOLDING

Folding in the region falls into distinct groups: folding affecting the younger cover, and tighter folding affecting Carboniferous older cover and generally associated with underlying reactivated and reversed early Carboniferous (Tournaisian–Visean) syndepositional normal faults, occurring in three main belts:

- Ribblesdale fold belt and Craven fault belt
- West Yorkshire and East Midlands domain
- Pennine line

Finally there is also folding associated with the pre-Carboniferous basement rocks of the Craven inliers.

Younger cover in the eastern part of the region is not significantly affected by folding, the area lying over the eastern England platform across which regional dips rarely exceed 2°. Open fold structures do affect younger cover (Permo-Triassic) in the west of the region.

Folding of the older cover in the region is largely restricted to those areas in which Tournaisian–Visean extensional basins developed, the major basin-bounding normal faults being reactivated and partially reversed (or, more commonly, obliquely reversed) during Variscan basin inversion in latest Carboniferous times. Therefore, in contrast to the major synrift normal faults, Variscan inversion structures in the region, which lie at much shallower structural levels, can be readily discerned at outcrop.

This is particularly the case with the Ribblesdale fold belt (Figure 14) in the Craven basin, which suffered significant Variscan folding due to its position between the rigid Lake District block to the north, the Askrigg block to the north-east and the central Lancashire high to the south. The fold belt extends east-north-east for at least 80 km and is up to 25 km wide. It comprises an *en échelon* set of east-north-east-trending, mostly asymmetrical anticlines, generally between 5 and 10 km in length, with broad intervening synclines that mark the inversion axis of the Craven basin. The fold belt includes the Pendle Monocline and the Lothersdale, Skipton, Whitewell, Thornley, Plantation Farm, Sykes, Catlow, Dinkley, Slaidburn, Clitheroe, Wheatley, Gisburn–Swinden, Middop, Thornton, Bolton and Nicky Nook anticlines. They formed as a result of the oblique reversal of earlier Tournaisian–Visean normal faults during the Variscan Orogeny. Variscan uplift here was greater than anywhere else in the region, and may locally have exceeded 4000 m.

The southern margin of the Ribblesdale fold belt is marked by the Pendle Monocline. Traceable at the surface for about 40 km, it faces south, and affects mostly Namurian and Westphalian strata and is the largest individual inversion structure in the region, having been formed by reversal of the underlying northerly downthrowing, basin-bounding Pendle Fault. The fold amplitude is more than 1000 m along much of its length and locally up to 2000 m. In the Clitheroe district, nearly 3000 m of Tournaisian–Visean to Westphalian strata, dipping south at 50º to 70º, crop out in a distance of less than 5 km. Locally, the fold has a well-defined axial crest with significant development of a northern limb, forming subsidiary structures such as the Dinkley and Lothersdale anticlines, the latter passing eastwards into the major Skipton Anticline.

At outcrop, the northern margin of the Ribblesdale fold belt largely corresponds to a series of Variscan folds and reverse faults associated with reversal of the subsurface faults of the Bowland Line–Doeford–Whitwell–Thornley faults and the North Craven Fault. Typical inversion structures of this type include the Plantation Farm Anticline and the Sykes Anticline. A set of *en échelon* anticlines with intervening synclines occur within the Ribblesdale fold belt, marking the main inversion axis of the Craven basin and the deepest (oldest) exhumed Tournaisian–Visean strata, some beds of which display an axial plane cleavage. Seismic reflection evidence indicates that the asymmetrical anticlines formed by reversal of earlier normal faults. Good examples include the Clitheroe, Wheatley, Gisburn–Swinden, Middop and Thornton anticlines, all of which may be associated with reverse faulting.

In the very north-west of the region, the easterly facing Hutton Monocline is associated with the north–south-trending Quernmore–Kendal Fault on the southern margins of the southern Lake District high. It is thought to have a similar origin to structures in the Dent fault zone, involving Variscan reversal of a Tournaisian–Visean, westerly downthrowing, normal fault and the formation of a steep to overturned eastern limb (Brandon et al., 1998; Aitkenhead et al., 2002).

From the main Ribblesdale fold belt, folding extends north-eastwards across the region associated with the Craven fault system (Figure 14), seen in the Eshton, Hetton, Grindleton, Skryholme, Skipton, Cayton Gill, Ellenthorpe and Sessay anticlines, particularly the North Craven Fault in the east of the region. The folds are generally asymmetrical, with steep northern limbs and amplitudes of 200–300 m (Kirby et al., 2000). Closely related to this group of folds is the Harrogate Anticline, some 10 km to the south. It is mapped at surface as an east-north-east-trending, asymmetrical, periclinal fold with a steep north-west limb dipping at up to 80˚ and cut by a high-angle reverse fault. Minor folds parallel to the main fold are superimposed on the main fold and it carries many characteristics suggestive of oblique, Variscan compression (Kirby et al., 2000).

Another area of significant Variscan folding is in the south-east of the region, where several anticlines and monoclines (for example, the Don Monocline) affect the Edale basin, the Widmerpool gulf, the Gainsborough trough and the East Midlands platform (Figure 14). Structures include the Longstone Edge, Calow–Brimington, Ashover and Crich anticlines. Farther east, important inversion structures, exemplified by the Eakring Anticline, are concealed beneath the younger cover. These structures are somewhat enigmatic because they are not, in general, associated with the reversal of major basin-bounding synrift faults, but formed by reverse reactivation of smaller, intrabasin faults. Their dominant north-west trends are perpendicular to the structures of the Ribblesdale fold belt, and closer in orientation to the folds of the Pennine–Dent line and associated structures.

Associated with the Stockdale Fault in the north of the region are a series of *en échelon* monoclines and anticlines within the hanging-wall block of the fault, which together constitute the Stockdale disturbance (Dunham and Wilson, 1985).The folds are typically a few kilometres in length with generally steeper southern limbs and amplitudes approaching 100 m. They are presumed to have formed during Variscan reversal of the subsurface down-to-north, normal fault (Kirby et al., 2000).

The prominent north-trending Pennine line or axis is a generally asymmetrical fold, with steep dips on its western flank and gentle dips on its eastern one. In the north, a prominent monocline faces west, but when traced southwards, the structure takes on a more anticlinal form. Further south, folding becomes more apparent and spread over a wider area, with the generally asymmetrical, west-verging Mossley Anticline, and a series of *en échelon*, northerly trending anticline/syncline fold pairs well seen at outcrop, including the Goyt Syncline and Ecton, Mixon–Morridge, Edgemoor, Longhill, Macclesfield Forest, Taddington, Todd Brook, Minn and Dovedale anticlines (Evans et al., 2002; Aitkenhead and Wray, 2002).

Folding of the younger cover in the west is of a much more open, gentle nature in comparison. The principal folds are the Elswick dome and Kirkham and Pressall synclines. The folds show no association with the dominant north-westerly trend that characterises the Ribblesdale fold belt in the Carboniferous rocks to the east. Instead, they seem to have formed during Permo-Triassic times along a north-north-easterly trend that was probably controlled by fault lines inherited from the underlying early Palaeozoic basement (Aitkenhead et al., 2002).

Much stronger and more pervasive folding is seen in the pre-Carboniferous (Ordovician–Silurian) basement rocks of the Craven inliers on the southern margin of the Askrigg block, between Ingleton and Malham in Yorkshire (Figure 14). The strata in the Craven inliers are strongly faulted, cleaved and folded, being disposed about east-south-east-plunging folds: the Studdrigg–Studfold Syncline, and the Austwick and Crummack anticlines. Because of its structural complexity and minimal surface outcrop, the nature of the Caledonian basement is poorly understood but there are affinities with strata of the southern Lake District.

5.5 UNCERTAINTY

As stated above, seismic reflection data coverage 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 younger cover (Permo-Triassic crop) has the best density of coverage, whilst areas underlain by basement massifs and Tournaisian–Visean intrabasinal highs to the north and south of the region have no coverage due to their lack of hydrocarbon prospectivity. Areas of younger older-cover rocks (Namurian–Westphalian strata) have generally poor coverage, except where underlain by thicker Tournaisian–Visean basin successions east of the Pennines.

A fault is recognised as being present because distinctive units of strata are offset by varying amounts relative to one another, both horizontally (slip) and vertically (throw), and in a normal or reverse sense. Surface evidence is based on geological mapping, where faults may be seen at crop, or their presence, attitude and location may be ascertained from mapping offset formational boundaries, for which the degree of confidence is in turn dependent upon the nature and degree of confidence in mapping those adjacent formations at crop. It is important to understand the nature of geological faults, and the uncertainties which attend their mapped position at the surface. Faults are planes of movement along which adjacent blocks of rock 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. The portrayal of such faults as a single line on the geological map is therefore a generalisation.

The presence, subsurface location, attitude and displacement of faults, may be evidenced by geophysical techniques. These techniques themselves carry varying degrees of confidence, depending on their varying 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, generally acquired during hydrocarbon and coal exploration, provide greater resolution and thus permit more accurate identification, location and mapping of fault(s) and other structures in the subsurface. Areas where there is limited or no subsurface data carry the greatest degree of uncertainty in terms of the presence, location and nature of subsurface structures such as faults. Across the region, acquisition of seismic reflection data are variable in extent, which thus provides varying levels of confidence in the identification, location and nature of major structures, particularly those concealed in the subsurface. The areas of Permo-Triassic and Tournaisian–Visean to Namurian strata of more basinal origin have reasonable to good coverage. However, the coalfield areas and those areas underlain by or with early Palaeozoic strata at crop have very sparse to no seismic coverage. In these areas ,confidence in the location of faults is thus limited to outcrop and other geophysical data with a lower resolution (gravity and aeromagnetic). Seismic coverage is dense in parts along the eastern margin of the region. Data is less tightly spaced across the western part of the region covering the Cheshire basin and Lancashire coalfield areas. The Derbyshire high and areas north of the North Craven Fault and in the centre of the region around Halifax, Bradford and Leeds are devoid of any seismic data. 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 Pennines 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 THE PENNINES REGION

There is some information related to groundwater in the depth range of interest, i.e. between 200 to 1000 m depth in the Pennines region. However, the majority of the information is related to the relatively shallow groundwater system that is currently exploited for groundwater resources, typically to depths of < 200 m. Since groundwater movement and chemical composition can vary significantly over short lateral and vertical distances, even in the depth range of interest, the level of uncertainty related to groundwater systems in the depth range of interest is high.

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The regional groundwater flow systems in the Pennines region 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, such as the Irish Sea coastline to the west of the region.

The GVS for the Pennines region (Table 3) divides rock units into three broad lithostratigraphical systems: basement rocks; older sedimentary rocks, and younger sedimentary rocks, and lists the principal aquifers. The oldest rocks in the region, Silurian and Ordovician basement rocks, only outcrop in the Craven inlier on the southern margin of the Askrigg block. Throughout the rest of the region they are typically found below the depth of interest (see Section 4.2) and so they receive very little direct groundwater recharge. The older Carboniferous sedimentary cover sequence crops out from the Peak District in the south, throughout the Pennines, to the Yorkshire Dales in the north of the region. On the flanks of this higher ground, the younger Permian and Triassic sequences dip to the east and west respectively. All the aquifer units within the older and younger sedimentary sequences receive direct groundwater recharge across the region, except where they dip below regionally confining units such as mudstones of the Mercia Mudstone Group.

The regional groundwater flow in the cover sequence is broadly down dip towards the east and west, away from the Pennines, driven by head gradients from the high ground in the centre of the region towards the coast in the west and the relatively low-lying region to the east. This regional picture of groundwater flow is disrupted by the effects of extensive faulting and folding on subregional to local-scale hydrogeology. For example, hot springs and mineral springs are commonly associated with folding and permeable fault zones throughout the region, enabling groundwater to move up from depth. In some instances fault zones may act as recharge boundaries while others have also been shown to be major barriers to groundwater flow, compartmentalising groundwater flow in the zone of active groundwater exploitation (British Geological Survey, 1989).

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

- a groundwater system in the younger cover sequence of Permian and Triassic sedimentary rocks, with two distinct subregions: one to the east and the other to the west of the Pennines and high ground in the centre of the region
- a groundwater system within the older sedimentary cover rocks of Carboniferous age
- a relatively low-permeability system consisting of basement rocks and igneous intrusions of Silurian and Ordovician age

Rocks from the two cover sequences are found extensively in the depth range of interest across the region. There are a range of pathways (both known and potential) for groundwater movement between these two groundwater systems, principally associated with regional-scale structures and with anthropogenic features (e.g. boreholes and mines). For example, extensive mine workings in the Pennines Coal Measures Group have influenced water tables locally and increased permeability down to at least 250 m also allowing hydraulic contact between previously separated units. These potential pathways for groundwater movement between units and groundwater systems are discussed after a description of each of the three groundwater systems.

6.3.1 Hydrogeology of the younger sedimentary cover

The younger sedimentary cover sequence consists of the Mercia Mudstone Group; the Sherwood Sandstone Group (a principal aquifer and the most important source of groundwater in the region) and the underlying Kinnerton Sandstone Formation; the Cumbrian Coast and Appleby groups (the latter being a principal aquifer) in the west of the region, and the Lenton Sandstone Formation and Zechstein and Rotliegendes groups (principal aquifers) in the east. Where present, the Mercia Mudstone Group confines the underlying Sherwood Sandstone Group (British Geological Survey, 1989).

6.3.2 Hydrogeology of the Mercia Mudstone Group

The Mercia Mudstone Group is not usually considered to be an aquifer (Jones et al., 2000), and any groundwater-bearing potential is derived from the interbedding of low permeability mudstones with more permeable siltstones and sandstones (‘skerries’) (Aitkenhead et al., 2002). Skerries are present throughout most of the sequence except the uppermost Blue Anchor Formation (not present in the Lancashire basin). Thicker sandstone horizons are more common in the basal part of the sequence, such as the Tarporley Siltstone Formation of Nottingham and Cheshire, which can form locally important aquifers. In these formations groundwater can be in hydraulic continuity with the underlying Sherwood Sandstone aquifer (Jones et al., 2000).

There is little information about the hydrogeological properties of the mudstones and evaporites in the Mercia Mudstone Group in the depth range of interest (Jones, et al., 2000). In the east, some groundwater is obtained from zones of partial dissolution of gypsum bands that have formed cavernous horizons (Allen et al., 1997). Groundwater in the unit in the interval of active exploitation is hard, highly mineralised and nonpotable, and, to the west of the Pennines, the Mercia Mudstone Group is only rarely used because it is commonly brackish or saline due to the dissolution of halite (Aitkenhead et al., 2002). In the Nottingham area it is more potable although very hard (Howard et al., 2009).

6.3.3 Hydrogeology of the Sherwood Sandstone Group

The Sherwood Sandstone Group is a principal aquifer and the most important source for groundwater resources in the region. In the east, it crops out from the Teesside coast to south Nottinghamshire and dips shallowly to the east from outcrop to a depth of about 400 m in the east of the region. In the west, the group dips to the west (in Merseyside and Lancashire). Because of extensive faulting, it is present to depths of nearly 1000 m. It is also present in the Cheshire basin, from the surface to depths of more than 2000 m. The overlying Mercia Mudstone Group often confines the Sherwood Sandstone Group aquifer on both sides of the Pennines (Aitkenhead et al., 2002).

The sandstones are predominantly poorly cemented, with high intergranular permeability (Allen et al., 1997). Grain size and primary intergranular permeability decrease northwards (Aitkenhead et al., 2002). Fracture flow can also be important in the better-cemented and finer-grained strata (Aitkenhead et al., 2002). The presence of fractures enhances permeability in the depth interval of active groundwater exploitation (Aitkenhead et al., 2002) and particularly in the north where intergranular permeability is lower (Allen et al., 1997). Faults range in hydraulic character from low-permeability features (Allen et al., 1997) that dissect the aquifer into distinct blocks to highly permeable features that act to focus recharge (Aitkenhead et al., 2002). The aquifer characteristics of the sandstone vary east and west of the Pennines and are described separately.

6.3.4 Hydrogeology of the Sherwood Sandstone Group and Lenton Sandstone Formation to the east of the Pennines

To the east of the Pennines, the group comprises the Chester Formation (formerly the Nottingham Castle Sandstone Formation). In the north, the aquifer is generally underlain by the low-permeability Roxby Formation (the former Upper Permian Marl) of the Zechstein Group, and it is confined by the Mercia Mudstone Group in the east. In Nottinghamshire and South Yorkshire, the Chester Formation is underlain and in hydraulic continuity with the Lenton Sandstone Formation, in part a lateral equivalent of the Permian Roxby and Edlington formations (Allen et al., 1997; Aitkenhead et al. 2002; Ambrose et al., 2014). The Lenton Sandstone Formation, although a separate unit underlying the Triassic Sherwood Sandstone Group and a lateral equivalent of the Roxby Formation of the Zechstein Group, is grouped with the Sherwood Sandstone Group in this region in NGS3D.

In Yorkshire, fracture flow is conceptualised to be limited to the upper 100 m (approximately) of the aquifer, whereas in the Midlands fractures are thought to be open to depths of at least 200 m bgl (Allen et al., 1997). Fracture systems influence regional groundwater flows in areas that have been undermined (for example by coal mining in the Nottinghamshire area) (Allen et al., 1997) or where there has been subsidence related to evaporite dissolution at depth (for example between Doncaster and Catterick) (Aitkenhead et al., 2002). At the western edge of the eastern outcrop, subsidence has occurred due to dissolution of gypsum in the underlying Zechstein Group (Allen et al., 1997). There is a general increase in permeability from the north towards the south (Allen et al., 1997). The confined aquifer generally has a relatively low permeability, attributed to intergranular flow and the closure of fractures due to overburden of 200 m of Mercia Mudstone Group strata (Allen et al., 1997).

Groundwater flow is generally eastwards with water movement down dip (Andrews and Lee, 1979), although high abstraction rates now dominate local groundwater flow in the depth interval of active exploitation (Allen et al., 1997). Groundwater in the Sherwood Sandstone Group aquifer of the east of the region is commonly of calcium bicarbonate type (Howard et al., 2009). Elevated concentrations of SO_4 from the dissolution of anhydrite and gypsum in the underlying mudstones may be encountered in Yorkshire (Aitkenhead et al., 2002). Groundwater in the unconfined, actively exploited aquifer is predominantly modern (Howard et al., 2009). However, a near-continuous recharge and reaction sequence has been documented to a depth of around 500 m (east of 30 km from outcrop) for the last 100 000 years (Edmunds and Smedley, 2000). The transition from freshwater to water of increased salinity under confined conditions beneath the Mercia Mudstone Group varies from south to north; salinity remains low for over 10 km down dip in the Nottingham area, becoming older and increasingly saline 20–30 km to the east at Lincoln, whereas in North Yorkshire the transition occurs only a few kilometres down dip (Allen et al., 1997). At a depth of around 500 m (east of 30 km from outcrop) there may be a discontinuity where more saline groundwaters, probably in excess of 1 Ma are encountered (Edmunds and Smedley, 2000) corresponding to a lack of recharge during the last (Devensian) glaciation. These palaeowaters remain effectively isolated from the active present day meteoric flow system (Edmunds et al., 2001).

6.3.5 Hydrogeology of the Sherwood Sandstone Group and Kinnerton Sandstone Formation west of the Pennines

Across Cheshire, south Lancashire and the Fylde, the Triassic Sherwood Sandstone Group and the underlying Kinnerton Sandstone Formation (spanning the Permian–Triassic boundary) in the south-west of the region, overlie the Manchester Marls Formation of the Cumbrian Coastal Group. The latter provides a hydraulic separation from the underlying Collyhurst Sandstone Formation of the Permian Appleby Group (Aitkenhead et al., 2002), except in the south of the Cheshire basin where the Manchester Marls Formation is not present (Downing and Gray, 1986). The Sherwood Sandstone Group is covered by the confining Mercia Mudstone across much of the Cheshire basin.

The Sherwood Sandstone Group comprises the Helsby Sandstone, Wilmslow Sandstone and the Chester formations, all of which are in hydraulic continuity (Allen et al., 1997). Mudstones are most common in the Chester and Helsby Sandstone formations. These are thin and laterally discontinuous and so unlikely to affect regional hydrogeology (Allen et al., 1997). The Kinnerton Sandstone Formation is characterised by generally pebble-free, fine to medium-grained sandstone that cannot easily be separated from the underlying and lithologically similar Bold Formation.

The Chester Formation is the most significant aquifer unit, and fracture flow dominates in the near surface (Allen et al., 1997). The Wilmslow Sandstone Formation is poorly cemented and intergranular flow is more significant (Allen et al., 1997). The Helsby Sandstone Formation is also well cemented and is a poor aquifer relative to the Wilmslow Sandstone and Chester formations (Allen et al., 1997). The frequency of open fractures in the group in the Merseyside region reduces markedly with depth, and the aquifer is considered to consist of two zones: an upper, relatively permeable, fractured zone to a depth of about 200 m, and a deeper, relatively low-permeability zone extending to the base of the Sherwood Sandstone Group (Allen et al., 1997). Across the Fylde, groundwater is abstracted from the Sherwood Sandstone Group for industrial purposes, although potable water has previously been reported to have been obtained from depths of about 250 m (Wray and Wolverson Cope, 1948).

Groundwater chemistry data from the Sherwood Sandstone Group is highly variable (Griffiths et al., 2005 and may be affected by faulting, evaporite deposits, cements type and degree of cementation, recharge through superficial deposits and the degree of confinement and pollution (Griffiths et al., 2005). Faulting and clay-rich horizons have compartmentalised the aquifer, causing considerable spatial heterogeneity of most chemical parameters and solute concentrations (Griffiths et al., 2005). A porewater profile for a borehole at Chat Moss, south-west of Manchester, shows a freshwater/saline interface at 190 m depth (Griffiths et al., 2005). The Triassic infill of the Cheshire basin is not overlain by younger rocks and it therefore has hydrogeological characteristics intermediate between those of 'concealed' basins and freshwater aquifers (Darling et al., 1997).

The freshwater/saline interface occurs at different depths in the Cheshire basin. Saline water present at 800 m below Chester (Allen, et al., 1997) is inferred to be due to longer-residence groundwaters, probably recharged in the late Pleistocene. The presence of this old, saline water suggests that groundwater flow may be limited below this depth (Allen et al., 1997). However, this water is now being brought to the surface in places by the reversal of hydraulic gradients through groundwater exploitation (British Geological Survey, 1989).

6.3.6 Hydrogeology of the Permian sediments

6.3.6.1 Hydrogeology of the Zechstein Group

The Zechstein Group (including the former ‘Magnesian Limestones’), a principal aquifer, occupies a narrow north–south outcrop from Sunderland to Nottingham, along the east side of the Pennines, dipping towards the east beneath the Sherwood Sandstone Group and overlying either the early Permian Rotliegendes Group or Carboniferous strata. It comprises two groundwater bearing units: the Cadeby and Brotherton formations (formerly the Lower and Upper Magnesian limestones respectively), separated by the Edlington Formation (formerly Middle Permian Marls) (Allen et al., 1997). The aquifer is developed for public water supply in

Yorkshire and further south towards Nottingham (Allen et al., 1997). The Cadeby Formation thickens and increases in importance as an aquifer to the north and down dip to the east from Worksop, but wedges out to the south. The importance of the Brotherton Formation as an aquifer also decreases southwards, due to lateral facies variations. To the north of Doncaster, the aquifer is confined by the Roxby Formation (also Zechstein Group). However, this becomes progressively sandier to the south, and around Worksop it passes into the sandstones of the Lenton Sandstone Formation (Allen et al., 1997; Aitkenhead et al., 2002). The Edlington Formation maintains a slight head difference between the two limestones although there is some hydraulic continuity, and many boreholes penetrate both limestones, therefore, the two formations (where both are present) are generally regarded as a single aquifer (Allen et al., 1997).

There is little hydraulic information about the units in the depth range of interest. The permeability of the limestones and dolostones depends on fracturing (Allen et al., 1997). The limestones may have substantial permeability where the fracture frequency is high (Allen et al., 1997), however, some faults restrict groundwater movement, such as across the Bramham Park–Tadcaster and the Bramham–Hazelwood faults (Allen et al., 1997). The quality of groundwater within the Cadeby and Brotherton formations is variable (Besien and Pearson, 2007). Generally, groundwater at outcrop is very hard and in the northern part of the aquifer groundwater may be affected by the dissolution of minerals from the Edlington Formation. The Edlington Formation thins southwards and is overlain then replaced farther south in the Nottingham area by sandstones of the Lenton Sandstone Formation.

6.3.6.2 HYDROGEOLOGY OF THE ROTLIEGENDES GROUP

The Rotliegendes Group, a principal aquifer, includes the Permian Basal Breccia, Basal Permian Sands Formation, Basal Permian Sandstone and Yellow Sands Formation. The Permian Basal Breccia is present in pockets, especially on flanks of contemporary ridges near Richmond, Knaresborough and Wetherby, but generally < 2 m in thickness (Aitkenhead et al., 2002) is are proved at > 230 m below OD in boreholes to the east of Worksop (Smith et al., 1973). At outcrop this unit is replaced or overlain by the Basal Permian Sandstone or Yellow Sands Formation, up to 6 m in thickness. The unit is present along north-east-trending ridges and is up to 3 km wide and 10 km in length, reaching a maximum thickness of 46 m (although is more commonly 0–15 m in thickness (Allen et al., 1997)). South of Doncaster the sands are largely absent.

There is little hydraulic information about the units in the depth range of interest. The Basal Permian Sands Formation is highly permeable at outcrop, but thin and impersistent, and although normally incapable of providing a water supply, borehole yields of 1 l/s have been reported. In the east of the region, the sands are generally separated from the Zechstein Group limestones by the Marl Slate Formation, which acts as an aquiclude (Aitkenhead et al., 2002) and uncomformably overlies Carboniferous-aged rocks.

6.3.6.3 HYDROGEOLOGY OF THE OTHER PERMIAN GROUPS

In this region, the Cumbrian Coast Group is represented by the Manchester Marls Formation, mainly comprising mudstones, the depth and thickness of which are highly variable due to extensive faulting. The unit separates the aquifer of the underlying Permian Collyhurst Sandstone Formation of the Appleby Group from the overlying Sherwood Sandstone Group aquifer (note the Kinnerton Sandstone Formation, spanning the Triassic to Permian boundary, is described within the Sherwood Sandstone Group section and, therefore, any reference to the Sherwood Sandstone Group here includes the Kinnerton Sandstone Formation).

Westwards and southwards, this unit passes laterally into the sandstones of the Bold Formation in the western Cheshire basin (Aitkenhead et al., 2002) and cannot be differentiated from the sandstones above and below, bringing the Sherwood Sandstone and Collyhurst Sandstone Formation into hydraulic continuity in the extreme west of the Cheshire basin. There is limited hydrogeological information about this unit, particularly in the depth range of interest. The unit generally acts as an aquitard, however, limited water supply can be obtained locally from these rocks (Allen et al., 1997). Sandstones in the Bold Formation are permeable (Aitkenhead et al., 2002). Permeability of the Bold Formation is dominated by fracture flow (Walthall and Ingram, 1981; Allen et al., 1997).

The Collyhurst Sandstone Formation principal aquifer is generally confined by the Cumbrian Coast Group and so it is typically hydraulically separated from the overlying Triassic Sherwood Sandstone Group. The unit is either faulted against, or lies unconformably on, Carboniferous rocks (Allen et al., 1997). To the east, intense faulting permits a free interflow at many points with the Sherwood Sandstone Group higher in the sequence (Allen et al., 1997). In south Manchester and Stockport, groundwater exploitation is limited to the outcrop area (Allen et al., 1997). However, the Collyhurst Sandstone Formation is a locally important aquifer in the Cheshire basin (British Geological Survey, 1989). There is no hydrogeological information about the unit in the depth interval of interest in the referenced literature.

6.3.7 Hydrogeology of the older sedimentary cover

6.3.7.1 Hydrogeology of the Warwickshire Group

The Warwickshire Group is mainly present in the Cheshire basin. Some formations in this group are considered principal aquifers but these are not present in this region. The Warwickshire Group generally rests conformably upon the Pennine Coal Measures Group and is overlain unconformably by Permo-Triassic strata, typically the Permian Collyhurst Sandstone Formation principal aquifer in the west of the region. There is almost no hydrogeological information about the unit in the depth range of interest in the referenced literature. Water has been found to occur in the sandstones of the Warwickshire Group to depths of about 250 m, both in joints and the many fractures caused by mining subsidence. Mines below these depths are generally dry (British Geological Survey, 1989). Near the surface, groundwater resources in the unit are dependent on joint frequency and resources are often not sustainable due of a lack of direct recharge and the division of the aquifer into isolated blocks by extensive faulting and folding (British Geological Survey, 1989).

6.3.7.2 Carboniferous Limestone Supergroup

The Carboniferous Limestone Supergroup aquifer comprises a wide variety of rock types, including mudstones, siltstones and sandstones in addition to the limestones (Allen, et al., 1997). Except where it is at crop, it is overlain by shales and sandstones of the Craven and Millstone Grit groups, which can form an almost impermeable cover on the flanks of the Derbyshire dome (Edmunds, 1971).

The unit comprises thick limestones with interbedded limestones and mudstones. The Carboniferous Limestone Supergroup is considered a principal aquifer in the Peak District (Allen et al., 1997) and locally elsewhere (see reports for other regions). In general, there is little hydrogeological information and hydrogeological data should be regarded with caution (Allen et al., 1997).

Groundwater flows rapidly through a network of fractures, conduits and caves that have been enlarged by dissolution (Allen et al., 1997). On the scale of metres to kilometres, the hydrogeological characteristics of the aquifer are dominated by the conduit systems and the aquifer properties may be extremely unpredictable, particularly in the more karstic areas (Allen et al., 1997). Karst features are especially well developed in the Yorkshire Dales and the Peak District. The frequency and size of fissures commonly decrease markedly with depth, giving an effective aquifer thickness of only 50 to 80 m (Aitkenhead et al., 2002).

The impact of faults on permeability is difficult to predict, depending on factors such as the presence, amount and permeability of fault infill, and whether the fault provides a connection between groundwater bodies (Allen et al., 1997). It is likely that folding also influences groundwater flow by development of joints and faults, which may be zones of enhanced permeability (Allen et al., 1997). The unpredictability of the aquifer has meant that water use from it has been mainly from springs; boreholes are relatively rare. The resurgences of Peak’s Hole and Bradwell are the most important supplies from the unit in the area (Eden et al., 1957). Where the limestone is penetrated at depth, for example by hydrocarbon exploration boreholes, great variability in flow rates has been noted (Downing and Gray, 1986).

Flow velocity in the Carboniferous Limestone Supergroup will depend on the prevailing hydraulic gradient and size of the fractures. Tracer experiments have shown that groundwater flow velocity can be of the order of hundreds of metres per hour, with this flow depending on large, interconnected conduit systems (Allen et al., 1997). The direction of flow is also difficult to predict in the Carboniferous Limestone Supergroup aquifer. Drainage, particularly in the northern and eastern parts of the Peak District, has been substantially affected as a result of mining activities (Allen et al., 1997). Large quantities of ore and gangue have been removed along veins that followed the principal vertical fractures and bedding planes. This has increased east–west groundwater flows. In places the present water table may be several hundred feet lower than it was before commencement of mining and it may be irregular, having a local impact on flow directions (Edmunds, 1971).

Shallow groundwaters in the Peak District are generally potable, though hard, commonly being of calcium bicarbonate type. Where deeply buried by younger strata, the groundwater in the Carboniferous Limestone

Supergroup is commonly saline, in some cases excessively so (Aitkenhead et al., 2002) where circulation is restricted due to low permeabilities and/or the absence of a natural outlet.

Deep groundwater movement in the Carboniferous Limestone Supergroup is indicated by the negative temperature gradient between 450 and 575 m, recorded in the Eyam Borehole (Peak District). The anomalous temperature measurements in this borehole are attributed to relatively rapid movement of recharge water to considerable depths (Aitkenhead et al., 2002). There is also a decrease in salinity of the Carboniferous brines with depth (through the Pennines Coal Measures Group, Millstone Grit Group and Carboniferous Limestone Supergroup). Water fresher than sea water in all formations denotes the displacement of saline formation water by shallow, fresh groundwater. Thus the saline formation waters are being modified by freshwater recharge into the outcrop areas of Carboniferous rocks in the Pennines (Downing and Gray, 1986). Twelve pressure measurements are available for the Carboniferous Limestone Supergroup from deep hydrocarbon boreholes. They show no strong trend in hydraulic gradient (Downing and Gray, 1986).

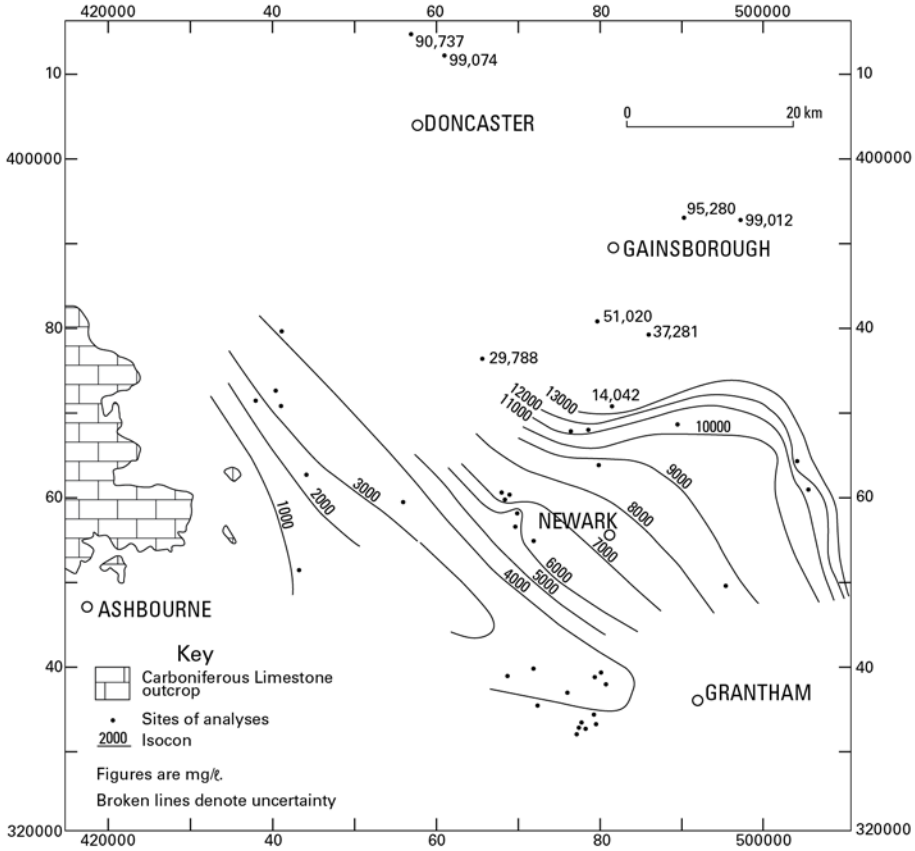


Figure 15 Variation in total dissolved solids of groundwaters in the Carboniferous Limestone Supergroup, from Downing and Howitt (1969). Reproduced from the Quarterly Journal of Engineering Geology, Geological Society of London.

6.3.8 Hydrogeology of the basement rocks

Silurian rocks, including the Windermere Supergroup and the Crummack and Horton formations, comprise a succession of sandstones and cleaved mudstones that outcrop in the Craven inlier on the southern margin of the Askrigg block, between Ingleton and Malham, Yorkshire, and around Liverpool, below the depth range of interest. There is no hydrogeological information about these units in this region in the reviewed literature.

There are a number of granite intrusions of Ordovician age modelled in the Pennines region, however, there is no hydrogeological information about these units in this region in the reviewed literature. Other Ordovician rocks in the region include turbiditic sandstones, siltstones and conglomerates of the Ingleton Group, present in the Askrigg block and Stainmore trough in the north of the region. Further south, undivided Ordovician rocks have been interpreted as extending beneath much of subsurface of the region, lying unconformably below Carboniferous strata over much of the region, except for the Wirral–Liverpool area where they underlie undivided Silurian rocks. Again, there is no hydrogeological information about these units in the reviewed literature.

6.4 EVIDENCE FOR CONNECTIONS BETWEEN GROUNDWATER SYSTEMS

6.4.1 Separation

There is little evidence for units that impart regionally significant hydrogeological separations between the three groundwater systems, however, there are two hydraulic separations within the groundwater system formed by the younger sedimentary cover sequence. To the west of the Pennines, the Manchester Marls Formation provides a hydraulic separation between the Sherwood Sandstone Group above, and the underlying Collyhurst Sandstone Formation of the Permian Appleby Group (Aitkenhead et al., 2002) except in the south of the Cheshire basin where the Manchester Marls Formation is not present (Downing and Gray, 1986). East of the Pennines, the Edlington Formation separates the Brotherton and Cadeby Formations (the former Upper and Lower Magnesian limestones) of the Zechstein Group (Allen et al., 1997). In the far south-east, and west of the Mercia Mudstone Group line of outcrop, the Mercia Mudstone Group confines the underlying aquifers in the younger sedimentary cover sequence.

6.4.2 Geological pathways

6.4.2.1 THERMAL SPRINGS

For the purposes of this report, thermal springs are defined as those with waters >15°C. There are a number of thermal springs in the region, in the Peak District, shown in Table 4 and on Figure 21. These waters are meteoric in origin but have been heated by circulation to appreciable depths below the surface (Downing and Gray, 1986). The thermal springs are all at the periphery of the Carboniferous Limestone Supergroup outcrop, from which it is inferred that the contact with the overlying Millstone Grit and Craven groups is the dominant factor controlling surface discharge (Downing and Gray, 1986). The springs issue from the plunging limb of the Derbyshire dome (Downing and Gray, 1986).

Table 4 Thermal sources and temperatures in the Pennines region, from Edmunds, 1971.

Thermal Centre	Source	Temperature (°C)	Discharge (l/s)
Buxton	St Anne’s Well	27.5	10.6
Stoney Middleton	Stoney Middleton Spring	17.7	1.3
Matlock	Fountain Bath	19.7	11.8
	New Bath Hotel	19.8	6.3
	East Bank of Derwent	17.4	0.5
	Meerbrook Sough	15.3	790.0

None of the thermal waters are less than 15 to 20 years old and their temperatures are likely to be maximum temperatures, not modified by dilution (Edmunds, 1971) as confirmed by geothermometry (Downing and Gray, 1986). Stable isotope measurements are consistent with modern, local recharge (Darling et al., 1997). They have low ^{4}He contents, indicating that their mean residence time is likely to be over 20 but less than 100 years (Downing and Gray, 1986). At Buxton, a minimum circulation depth of 600 m (Evans et al., 1979; Downing and Gray, 1986) has been inferred.

Groups of waters from the same thermal centre (cooler waters not included in Table 4) have similar chemical compositions (Edmunds, 1971). Water from Stoke Sough is similar to that from Stoney Middleton. In addition, a number of soughs also issue warmer than expected water, such as Warmbrook Sough south of Wirksworth. The temperature of the water at the outfall of the Meerbrook Sough varies between 13.5°C and 15°C (Frost and Smart, 1979). Water from Ball Eye Quarry Borehole (near Matlock) (13.6ºC) has been inferred to be thermal water diluted with recent water that has possibly been drawn in from the adjacent stream during pumping (Edmunds, 1971). Thermal water has also been encountered in the Eyam mines (Edmunds, 1971).

A conceptual hydrogeological model for the thermal waters in the Peak District is presented by Gunn et al. (2006). Buxton waters are shown as migrating to about1500 m depth in the Goyt Syncline before rising as a result of thermal effects, the flow possibly being focused by faulting at the limestone contact. Matlock-type waters are shown as migrating to around 800 m depth to interact with evaporite deposits. The 1–1.5 km depth inferred for the thermal flow at Buxton is comparable to the thickness of strata including Namurian (Millstone Grit and Craven groups) and Westphalian (Pennine Coal Measures Group) clastic sediments (approximately 1400 m (Aitkenhead et al., 1985)) overlying the limestone in the Goyt Syncline to the west of Buxton. The water chemistry and depth of flow do not require the thermal waters to have moved outside of the known Carboniferous Limestone Supergroup sequence. In the White Peak, the discharge of the deep flow component is controlled regionally by the lowest outcrop of limestone in the Derwent valley. The discharge of Matlock-type thermal waters from mine adits results from the local lowering of groundwater head by the driving of the adit and consequent upconing of the deeper thermal water. Deep, regional, thermal flow constitutes five per cent of groundwater discharge from the Peak District limestone aquifer (Gunn et al., 2006).

6.4.2.2 KARST

There is extensive karst in the Carboniferous Limestone Supergroup of the Peak District and Yorkshire Dales. Nearly half of Great Britain’s known caves lie in the Yorkshire Dales. The Ease Gill Cave system is the longest in Great Britain with > 80 km passages (Waltham et al., 1997), and the Peak District hosts the largest unbroken area of cavernous karst in Britain in the Derbyshire dome, and is also known to have palaeokarst. The Giant’s Hole–Oxlow caves are the deepest in Derbyshire, reaching depths of 214 m, and the second deepest in Britain.

Collapse of the Brotherton Formation is possible, caused by dissolution of gypsum in the underlying Edlington Formation (Aitkenhead et al., 2002) and collapse breccia is common from Doncaster to Rippon (Allen et al., 1997).

6.4.2.3 FAULTS

Faults are known to affect aspects of the hydrogeology of the region. Over a range of scales, faults within the region may act to compartmentalise groundwater by reducing flow across the structures, while in other cases they may act to enable enhanced flow of groundwater and may be associated with localising flows from depth to surface springs. In the Sherwood Sandstone Group, faults typically act to compartmentalise groundwater flows, e.g. a low hydraulic conductivity fault at Sandon Dock, Liverpool, appears to restrict flow across it (Allen et al., 1997). In addition, faults may disrupt or enhance local groundwater flow by juxtaposing more or less permeable units either side of fault strands (Allen et al., 1997) and may localise flow to springs. For example, sandstones within the basal part of the Mercia Mudstone Group can be brought into hydraulic continuity with the Sherwood Sandstone Group through fault displacement. Faulting can offset marly layers, allowing increased fluid flow within the sandstones (Allen et al., 1997), and highly transmissive faults may act as recharge channels (Aitkenhead et al., 2002).

In the Zechstein Group Cadeby and Brotherton formations, there is restricted groundwater movement across the Bramham Park–Tadcaster and the Bramham–Hazelwood faults, which compartmentalise the aquifer. However, the Topcliffe Fault, North Yorkshire, and a fault near Eggborough locally enhance groundwater flow (Allen et al., 1997).

6.4.3 Anthropogenic pathways

There are high densities of boreholes greater than 200 m in depth in the region (greater than 200 m below NGS datum) (Figure 22). These have mainly been drilled for evaluation of the coal deposits on both sides of the Pennines, for the evaluation of salt and development of gas storage caverns in the west of the region and for both conventional and unconventional hydrocarbon exploration and exploitation. The areas of highest intensity of drilling are around Southwell, Nottinghamshire, and Preese Hall, Lancashire, with over 50 boreholes/km^2 in some areas.

The Pennine Coal Measures and Warwickshire groups have been extensively mined in the past for coal, iron and limestone. Deep coal-mining operations have taken place at depths up to about 800 m below NGS datum, with workings accessed by vertical shafts cut through the overlying rocks (see resources section). South of Leeds there are large areas on the east and west flanks of the Pennines with coal mines present at depths > 100 m below river base level (brbl); there are also small areas of metal mines > 100 m brbl in the centre of the Peak District and the Yorkshire Dales. The majority of boreholes with terminal depths > 200 m brbl coincide with heavily mined areas in the east and west of the Pennines, south of Leeds (see Section 8.2).

Mining for coal typically changes the hydrogeological regime of an area, increasing the permeability through worked seams and collapsed workings and the introduction of fracture systems (Aitkenhead et al., 2002). Mining has also made artificial connections between aquifers, disturbing many of the natural rest water levels (Frost and Smart, 1979). Large areas of backfilled, opencast sites have effectively sealed off many square miles of permeable outcrop from possible surface recharge (Frost and Smart, 1979). The construction of soughs and underground tunnels to remove water from mines has caused significant modification of underground flow patterns (Gunn et al., 2006).

Mining for ore and gangue from the Carboniferous Limestone Supergroup in the northern and eastern parts of the Peak District has substantially affected drainage as a result of mining activities (Allen et al., 1997) and increased east–west groundwater flows. In places, the present water table may be several hundred feet lower than it was before commencement of mining and it may be irregular, having a local impact on flow directions (Edmunds, 1971).

Salt has been mined in traditional ‘dry’ mines in parts of Cheshire near Northwich (at about 90 m depth) and in Lancashire near Blackpool (at 160 to 330 m depth). Solution-mined caverns are typically between 100 to 400 m below the surface. To the south of the region, specially designed and constructed solution-mined caverns are used for the storage of natural methane gas at depths between 300 and 730 m near Northwich in Cheshire (see resources section). There are very small mined areas near Fleetwood, crossing the southern boundary of the region, in which mines are present at > 100 m brbl.

Hydrocarbons have been produced from a wide variety of reservoir rocks and at several localities within this region. Small gas and oil fields are present in west Lancashire and parts of Nottinghamshire and South Yorkshire (see resources section). Gypsum layers have been mined near Selby in North Yorkshire. Subsidence hollows formed through the dissolution of gypsum are a feature of the Ripon area (see resources section).

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 Pennines 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 Pennines 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 overdeepening
- 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 on reaching the London area (Figure 16; RWM 2016b; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next one million years is open to conjecture (Loutre and Berger, 2000). This is because the impacts 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 consensus 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.

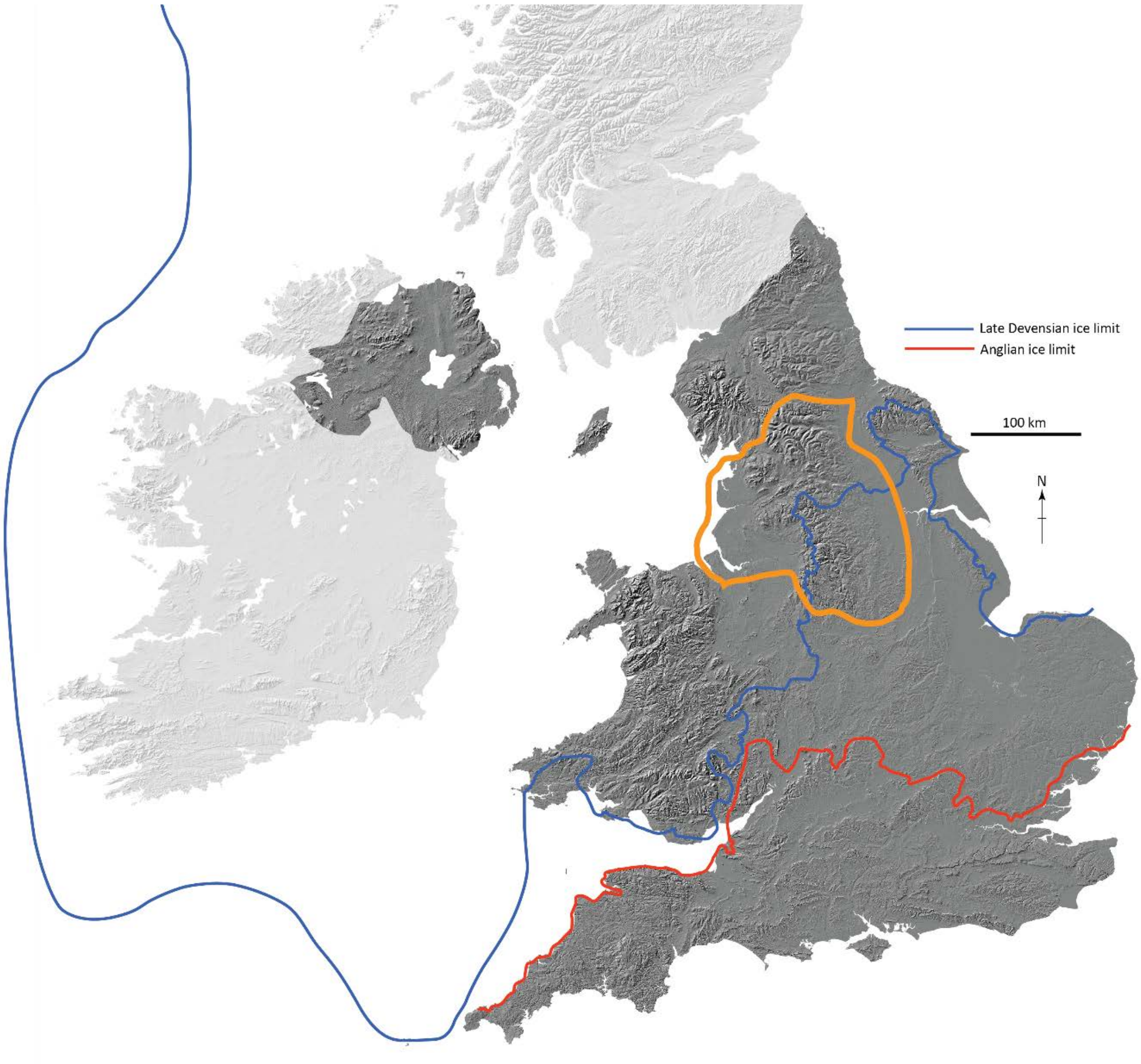


Figure 16 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and late Devensian (around 30 to16 ka). The location of the Pennines is delineated by the orange line. Produced using Copernicus data and information funded by the European Union — EU-DEM layers © EEA.

7.2.2 A regional perspective

Based upon geological evidence it is widely accepted that the region of the Pennines has been glaciated repeatedly during the past two and a half million years (Quaternary Period; Figure 16; RWM, 2016b, Loutre and Berger, 2000). During the late Devensian glaciation (around 29 000–15 000 years ago), the Pennines region was glaciated by the Irish Sea ice stream (in the west) and by several ice caps that formed over adjacent highland areas and coalesced to form a major sector of the last British–Irish ice sheet (Clark et al., 2012). This glaciation extended over much of the region including the Pennines, the Lake District and adjacent lowland areas. It was the second of two known continental-scale glaciations to affect the UK (Loutre and Berger, 2000). Direct evidence for earlier glaciations in the Pennines has not been preserved. However, the elevation of highland source areas in the Pennines coupled with their position relative to a prominent North Atlantic moisture source (the Gulf Stream) and other ice accumulation areas in northern England made it highly susceptible to being glaciated (Clark et al., 2012).

Over the next million years, assuming Britain is glaciated, it is likely that the Pennines region will experience highland glaciation and potentially lowland and continental glaciation (Clark et al., 2012, RWM, 2016b). This is because the elevation of its highland source areas and proximity to other ice sources in northern England, plus the Gulf Stream, make it highly susceptible to glacier inception (Clark et al., 2012). During all scales of glaciation, glacial overdeepening 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). A classic example of a glacially over-deepened, U-shaped valley is the Rawthey valley to the east of Kendal in the north of the region.

The formation of meltwater-incised valleys beneath glaciers (tunnel valleys) in lowland areas of the region 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). Numerous tunnel valleys have been identified in the region including beneath parts of the modern River Mersey. Their geometry locally reaches over 100 m wide and 50 m deep. Collectively, overdeepening 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, 2016)). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (French, 2007). The extensive coastline makes the western 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). Areas that may be susceptible to this include, for example, the Mersey and Ribble estuaries and the Fylde coastal plain.

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 (Figure 16), 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 the Pennines region 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 and lowland areas, future development of permafrost may be 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 17). 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 17). 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.

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).

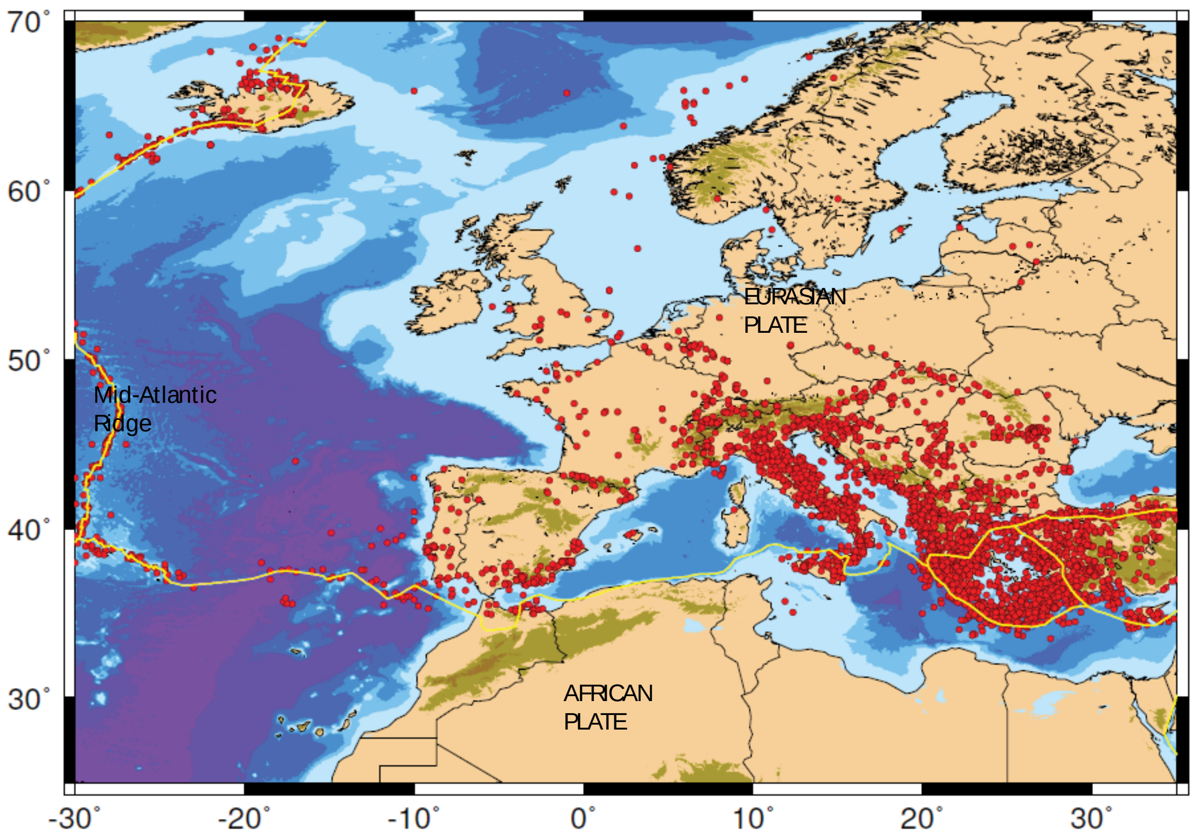


Figure 17 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

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 main shocks 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 18 shows a map of all of the main shocks in the 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.

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 18), 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).

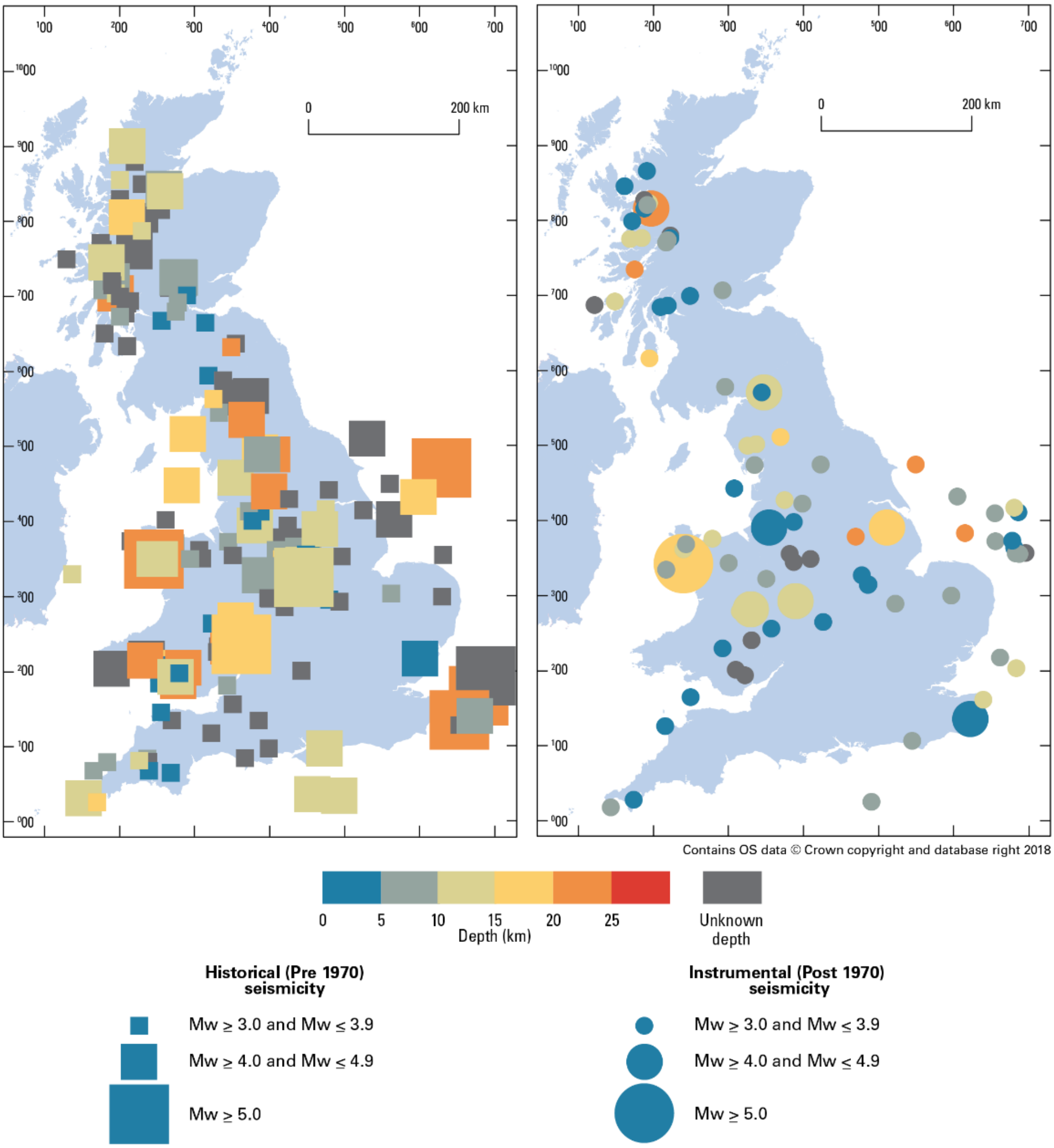


Figure 18 Distribution of the main shocks with Mw ≥3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

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 19 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.

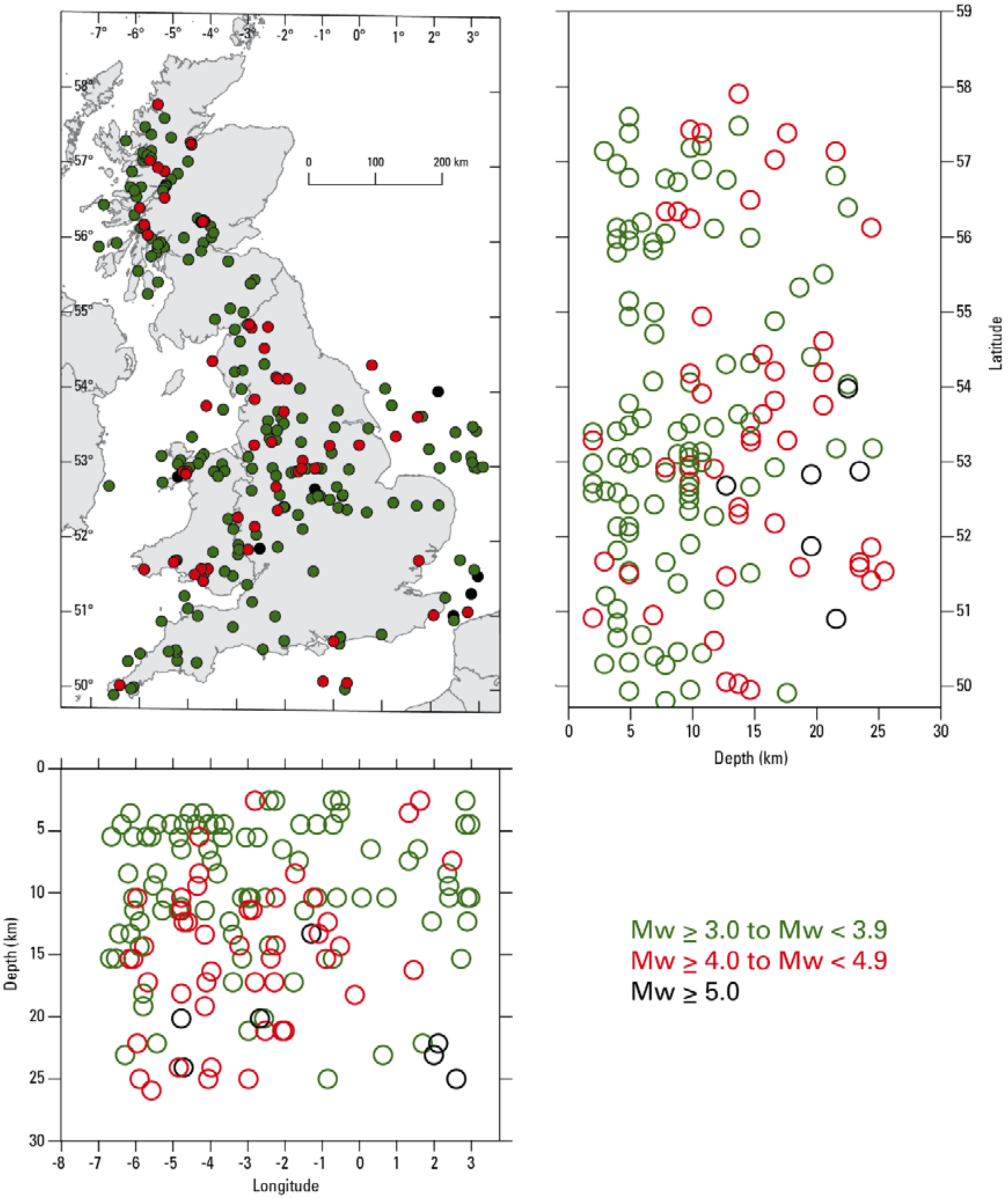


Figure 19 Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance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

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.

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 5) 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 20 shows earthquake activity in the Pennines region. Twelve earthquakes with magnitudes of 4.0 Mw or greater have been observed in this region in the last 500 years. There is some clustering of these events around Wensleydale on the east side of the Pennines in North Yorkshire, where three earthquakes with magnitudes of 4.0 Mw or greater have been observed, and to the south-east of the Peak District in Derbyshire. The largest observed event had a magnitude of 4.7 Mw and occurred in 1575. The 1944 Skipton earthquake had a magnitude of 4.5 Mw and was felt throughout northern and central England, and caused some minor damage at Skipton (Burton et al., 1984).

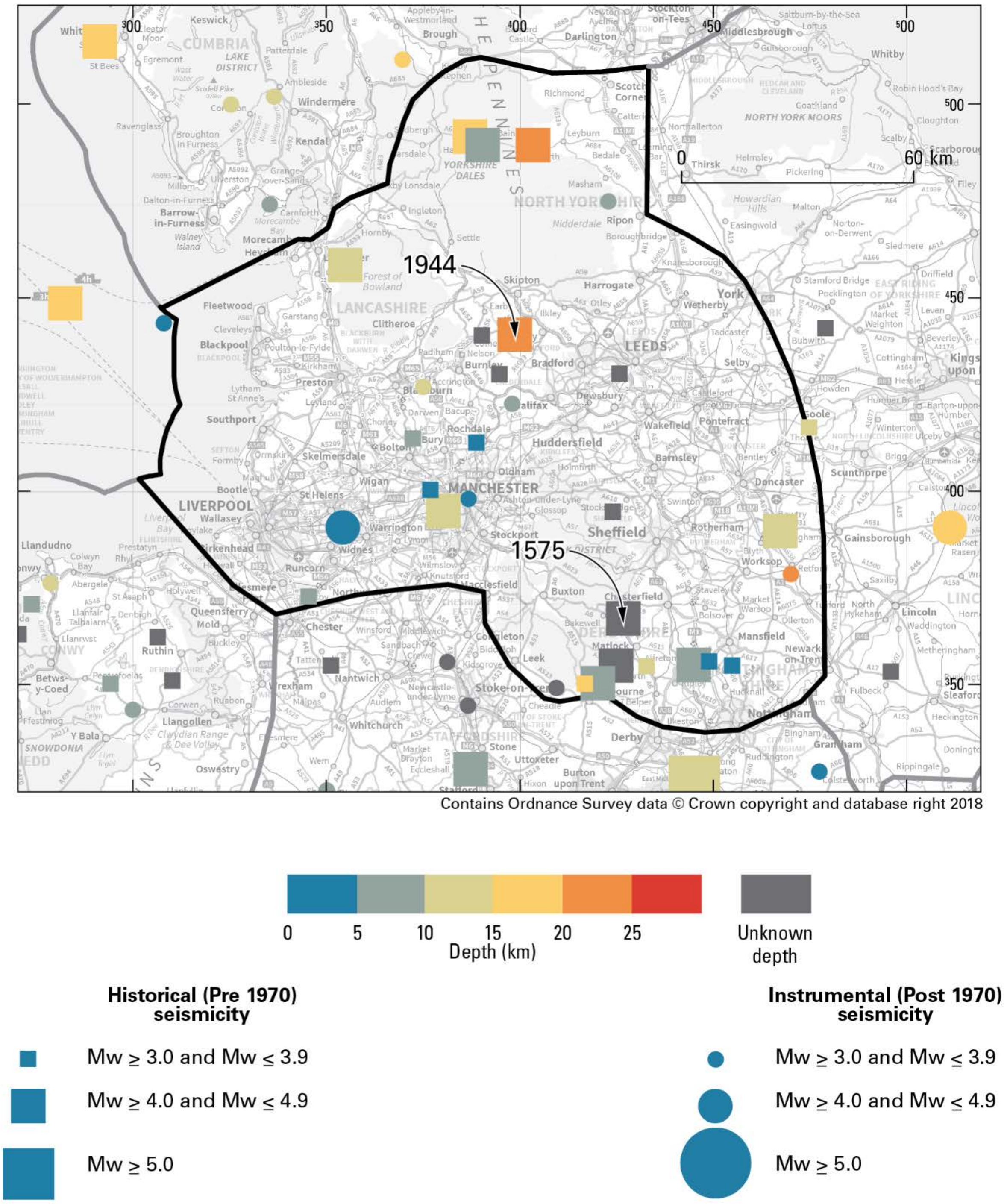


Figure 20 Historical and instrumentally recorded earthquakes in the Pennines region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 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 multibarrier 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 Pennines 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 PENNINES REGION

This region covers the upland areas of the Pennines from the Yorkshire Dales to the Peak District and the lowlands to both the west and east. It includes the large conurbations of Greater Manchester; Merseyside; the Lancashire towns including Preston and Burnley; the South and West Yorkshire cities of Bradford, Leeds and Sheffield; Derby, and Nottingham (Figure 2).

The region’s diverse landscape strongly reflects the composition and structure of the underlying bedrock geology. The strata seen at surface in the region are dominated by sedimentary rocks of Triassic, Permian and Carboniferous age, shown in Figure 2.The western and eastern margins of the region are underlain by

Triassic and Permian rocks that show a downward passage from mudstone-dominated to sandstone-dominated formations. Halites are locally present within the Triassic mudstones in the west of the region and limestones occur in the Permian succession in the east. Industrial and urban developments that flank the southern part of the Pennines are centred on the coal-bearing mudstones and sandstones of the late Carboniferous Coal Measures. The Yorkshire Dales and Peak District uplands are underlain by sandstones, mudstones and limestones of earlier Carboniferous age. The distribution of mineral resources in the Pennines region is shown in Figure 21.

8.3 COAL AND RELATED COMMODITIES

There are extensive coalfields in the region; Figure 23 shows the distribution of coal resources across the region. These have been heavily exploited on both sides of the Pennines, however, there are no longer any active deep coal mines. Despite the extensive mining, unexploited deep coal resources remain in both the east and west of the region.

Significant coal mining has taken place in the St Helens–Manchester–Burnley area of the south Lancashire coalfield. In this area, the Pennine Coal Measures Group dips to the south and mine workings become increasingly deep towards the southern edge of the region. To the west, the Pennine Coal Measures Group continues below Liverpool and The Wirral and is contiguous with the North Wales coalfield. There are no deep mines in operation in the south Lancashire coalfield. The last deep mine, Parkside in St Helens, west of Newton-le-Willows, was closed in 1993. Future potential areas for deep coal have been identified in the south of the region, between Widnes, Warrington and Salford, however, there are currently no efforts to further investigate or exploit these.

On the eastern side of the Pennines, coal has been extensively worked from the east Pennine and south Derbyshire coalfields. Here, the Pennines Coal Measures Group generally dips to the east and the deepest workings can be found at the eastern edge of the region where the Coal Measures occur at 1200 m below NGS datum. This area includes some of the largest and deepest mines that operated in the UK. Deep workings are concentrated around Doncaster, Rotherham, Bolsover, north-east Nottinghamshire and Pontefract. These deep mines began to close from the 1990s with Kellingley in South Yorkshire the last to close, in 2015. Significant resources of deep coal remain in the east of the region but there is no current interest in developing these.

There are currently two licences for coal mine methane and 14 licences for abandoned mine methane in the east Pennine and south Derbyshire coalfield areas, reflecting the extensive underground workings that exist here. There is also the UK's only operating coalbed methane site in the south-west of the region, Doe Green near Warrington, along with several petroleum exploration and development licences (PEDL) for exploration for coalbed methane between Chester and Manchester. There are no current licences for coal gasification in any of the coalfield areas.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

There are extensive areas of bedded Triassic salt in this region extending 20 km offshore, some of which have been mined, mainly by solutional methods, in the Preesall area in the west of the region and in the extreme south of the region near Northwich.

Gypsum has been worked at Sherburn Mine, near Selby, but only at shallow depths (less than 100 m below NGS datum).

Salt was produced at Preesall between 1889 and 1993. Extraction was initially by brine pumping using an early form of controlled brine pumping in which cavities are created in the salt bed. Soon after, rock-salt mining was introduced but it was subsequently abandoned in the early 1930s. The brine was used in salt manufacture and as a chemical feedstock. In later years, it was only used in the manufacture of chlorine and caustic soda by the electrochemical process at the Hillhouse works in Fleetwood. However, this plant closed in 1993, removing the need for brine. With a large and well- established salt industry in Cheshire, it is highly unlikely that production will resume at Preesall.

The salt deposits of the Cheshire basin have been worked in the extreme south of the region. Both brine wells at Holford and mining at Marston reached over 100 m below NGS datum. Salt-bearing strata are, however, ideally suited for the creation of storage cavities, notably for natural gas but also other materials.

Recent focus on salt resources in this region has been for storage rather than as a mineral resource; this is discussed in the gas storage section.

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 shallow depths across the region including high purity limestone, chert, black marble, pigments, glass sand and building stone.

8.6 VEIN-TYPE AND RELATED ORE DEPOSITS

Areas which 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.

The Askrigg area of the Yorkshire Dales forms the Askrigg block of the northern Pennine orefield and the Peak District. It also includes the southern Pennine orefield, which consists of the main orefield, the Crich inlier and the Ashover inlier. These orefields delineate the area where most of the known mineralisation is located, however, large parts of the orefields are not intensively mineralised and have not been extensively mined or mined to depths exceeding 100 m below NGS datum.

Because of the widespread distribution of mineral veins and the extent of past shallow mine workings in these areas, their mineral-resource potential may be re-evaluated in the future. 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 depth. The orefields have been worked extensively for lead over many centuries, since before the Roman occupation in the case of the southern Pennine orefield. More recently, both orefields have been mined for fluorite, with extensive deep workings for this commodity in the southern Pennine orefield, in particular in its northern part. Mining at one site, Milldam Mine, is currently ongoing. Mineral veins worked to depths greater than 100 m below NGS datum are shown on the Figure 21.

Two of the deepest mines in the southern Pennine orefield are at Mixon and Ecton, reaching around 270 m below NGS datum in the south-west of the region. Mining has ceased at these sites, which were worked for copper and lead, however, Ecton Mine is used for educational purposes. Extensive deep workings around Castleton, Stoney Middleton and Bakewell extend to just over 100 m below NGS datum.

Around Askrigg, the most intensively worked areas were around Grassington and Greenhow, and in the North Swaledale area, where deposits of lead ore in a linked system of faults were mined at Lownathwaite, Old Gang and Arkengarthdale Mines. Mining occurred to depths of up to 150 to 200 m below NGS datum.

The Craven basin (as shown by the letter V on Figure 21) is an area that is prospective for lead, zinc and fluorite mineralisation, but no commercial deposits have been identified as yet.

8.7 HYDROCARBONS (OIL AND GAS)

There are conventional gas and oilfields onshore in the region, on both sides of the Pennines. These are mainly oilfields to the east and gas fields to the west of the Pennines. Close to the coast in Morecambe Bay, the Lennox field of the East Irish Sea basin is about 8 km west-south-west of Southport and the Hamilton East field straddles the 20 km offshore buffer in the same direction from Southport. Several other gas fields occur a few kilometres beyond the 20 km coastline buffer. Onshore there is active gas extraction at Elswick. The Formby oilfield was exhausted in the 1960s, but a new operator has drilled some exploration wells recently. Gas has also been discovered by a borehole at Formby, but in sub-economic quantities.

To the west of the Pennines there are a few small gas fields to the east of Doncaster with extraction at the Hatfield site. Further south there are numerous small oilfields with producing boreholes in Nottinghamshire at Bothamsall, Egmanton, Farleys Wood and Kirklington, as well as numerous currently non-producing fields. Nottinghamshire has been intensively explored for oil and gas since before the Second World War. This is illustrated by the large number of exploration boreholes in the county. Large parts of Nottinghamshire are currently licensed for oil and gas exploration and it is likely that there will be further small oil discoveries in the future.

Large parts of the area have been identified as having prospectivity for shale oil or gas and an area near Blackpool is under active consideration for shale gas production. Exploration boreholes have been drilled penetrating shale gas resources at Grange Hall, Preese Hall and Becconsall. Testing has been carried out at the Preese Hall borehole but was stopped because the testing was linked to several nearby small seismic events. There are currently future plans for exploration in this area. Licences have also been granted by DECC for shale gas in north Nottinghamshire, but no drilling has yet taken place.

8.8 GAS STORAGE

The Pennines region offer potential for underground gas storage (UGS), both in bedded salt deposits and porous rock (depleted hydrocarbon fields). An UGS facility is operational at the depleted Hatfield Moors gas field, east of Doncaster, in the east of the region. Scottish Power is also evaluating the conversion of the nearby smaller depleted Hatfield West gas field for storage purposes, for which planning consent has been gained. The Hatfield Moors gas field was converted to a gas storage facility in 1998, with operations having commenced in February 2000, storing up to 121.8 mcm (4.3 bcf) of gas. The storage horizon is the Oaks Rock Sandstone, at a depth of around 424 m below NGS datum. The Hatfield West gas field is slightly shallower at about 394 m below NGS datum.

Potential for salt-cavern storage exists in the south of the region in the northern extension of massively bedded Triassic halites within the Cheshire basin. Storage facilities (Holford, Stublach, Hole House and the Hill Top Farm extension) already operate in caverns created in the Northwich Halite Formation in the northern areas of the adjacent Central England region. The same halite beds extend at shallower depths into the southern areas of this region and have been worked for brine in the Holford brine field.

In the north-west of the region, east of Fleetwood in Lancashire, brine has been extracted from the massively bedded Triassic Preesall Halite Member, which forms the Preesall salt field at depths between about 500 m depth and wet rockhead (where the salt is dissolving because it is in contact with fresh groundwater). A proposed scheme to develop a gas storage facility in solution-mined caverns gained planning consent in 2015 and would effectively tie up the remaining, deeper, unused areas of the salt field, beyond the existing brine field area. The same halite beds extend offshore into the East Irish Sea, where it is proposed to construct a 1500 mcm storage facility in these strata approximately 25 km offshore. The halite beds under consideration are at between 270 and 550 m below mean sea level (msl). Elsewhere the Preesall Halite Formation is at depths ranging from sea bed to around 600 m below msl, but generally at shallower depths in the offshore 20 km zone.

8.9 GEOTHERMAL ENERGY

The region is underlain in the south-west by the thick sedimentary succession of the Cheshire basin, including the Sherwood Sandstone Group brine aquifer and basal Permian sandstones. Regional mapping of the Cheshire basin has inferred that, in the deeper buried areas of the basin, the basal Permian sandstones could reach up to 4500 m depth, and potentially reach 100ºC at their base, with the base of the Sherwood Sandstone Group in excess of 80ºC. Although not nationally significant, the area has potential for local, low-enthalpy heating schemes.

Deeper targets would be the fracture networks of the Carboniferous limestones and sandstones, with formation temperatures potentially exceeding 140ºC. These targets have been proposed for exploitation for a district heating scheme in Manchester by GT Energy.

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 at the Markham Colliery, north-east Derbyshire, producing 20 kW of energy to heat local offices.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are extensive areas with clusters of deep (greater than 200 m below NGS datum) boreholes in the region (Figure 22). These have mainly been drilled for evaluation of the coal deposits on both sides of the Pennines, for the evaluation of salt and development of gas storage caverns in the west of the region and for both conventional and unconventional hydrocarbon exploration and exploitation. The areas of highest intensity of drilling are around Southwell, Nottinghamshire, and Preese Hall, Lancashire, with over 50 boreholes/km^2 in some areas. Over the coalfield areas there are rarely more than 5 boreholes/km^2 but the majority of the coalfields have been intensively drilled.

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 will not be 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 the NGS exercise (over 100 m). 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 laterally 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 over estimate 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.

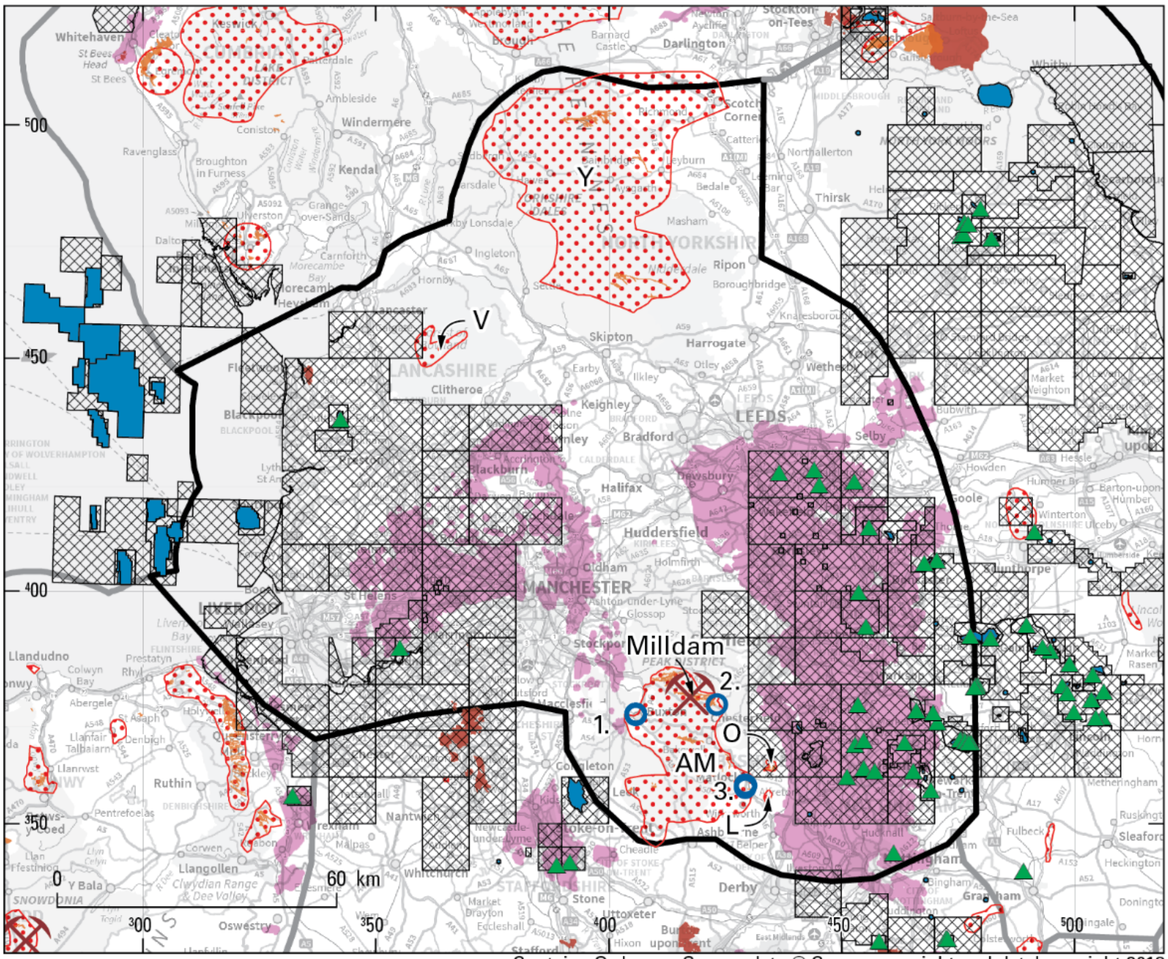
8.11.2 Mined extents

The areas of vein-type and related ore deposits shown on Figure 21 and 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 evaporate deposits is largely based on geological interpretation supported by seismic survey information and occasional boreholes. As such there is uncertainty about their distribution, which in some areas may be considerable.



Orefield	Map Label
Crich	L
Ashover	O
Craven Basin	V
Northern Pennine Orefield	Y
Southern Pennine Main Orefield	AM

Figure 21 Distribution of mineral resources in the Pennines 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 areas licenced for underground gas storage, 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

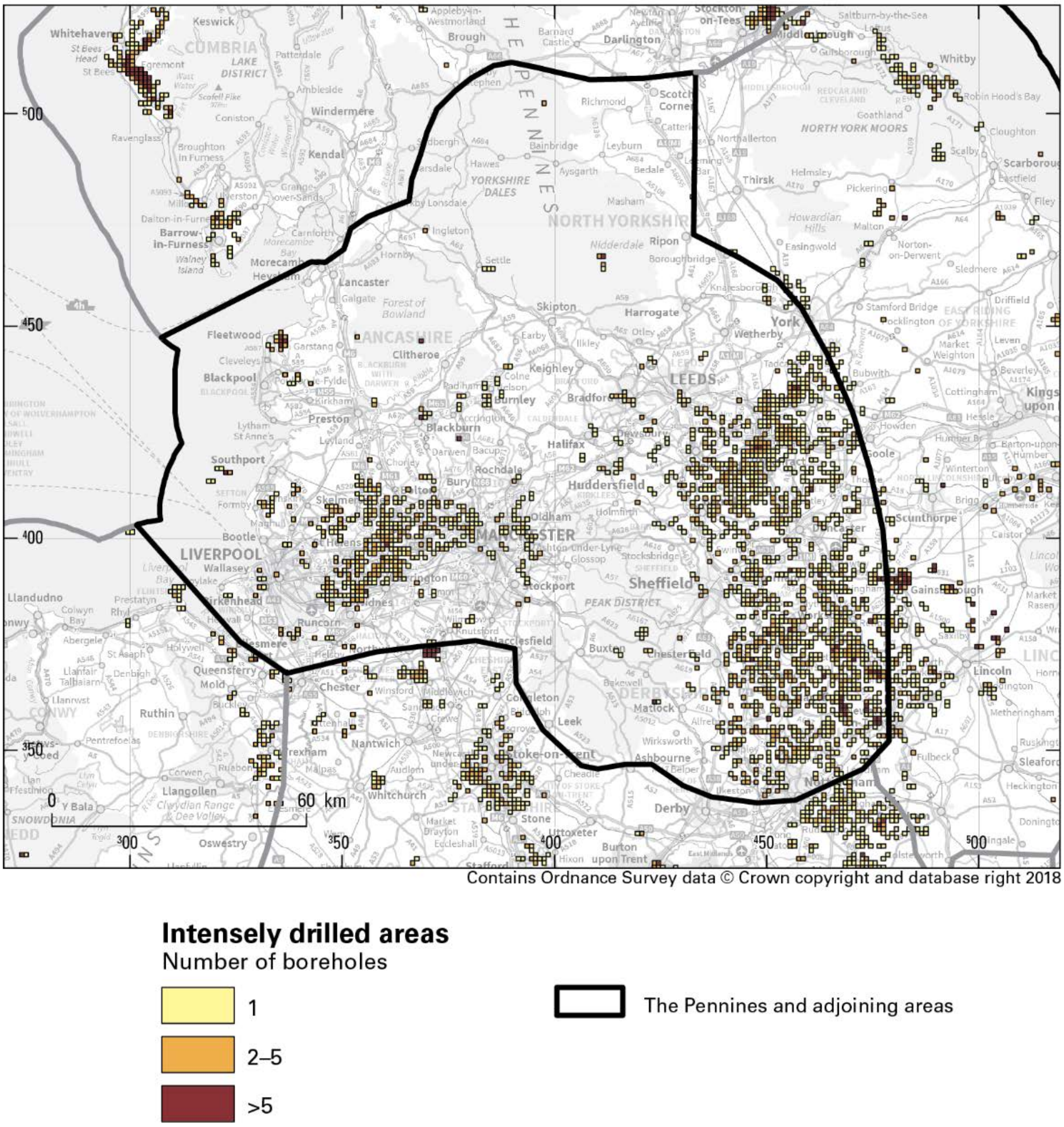


Figure 22 Location of intensely drilled areas in the Pennines region, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

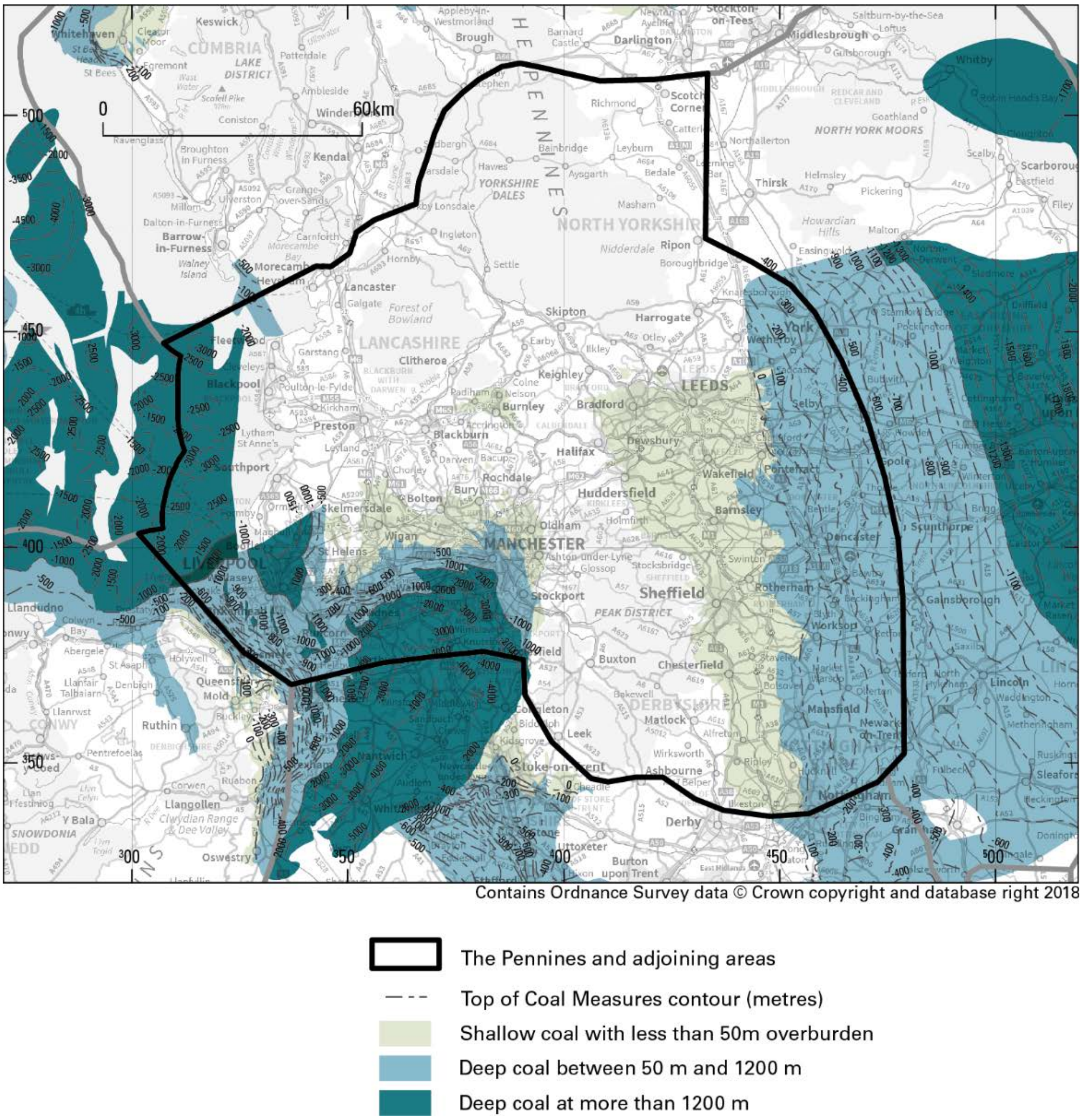


Figure 23 Distribution of coal resources in the Pennines region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

8.11.4 Hydrocarbons (oil and gas)

The hydrocarbon fields displayed on Figure 21 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 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 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 the surface. 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 database used records borehole length and not vertical depth. The BGS Single Onshore Borehole Index 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 overestimating maximum depth, and may 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 m').

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Resources

<u>Coal resources</u>

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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/