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National Geological Screening: Central England region

Minerals and Waste Programme

Commissioned Report CR/17/091

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MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/091

National Geological Screening: Central England region

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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 Central England region to underpin the 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 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.

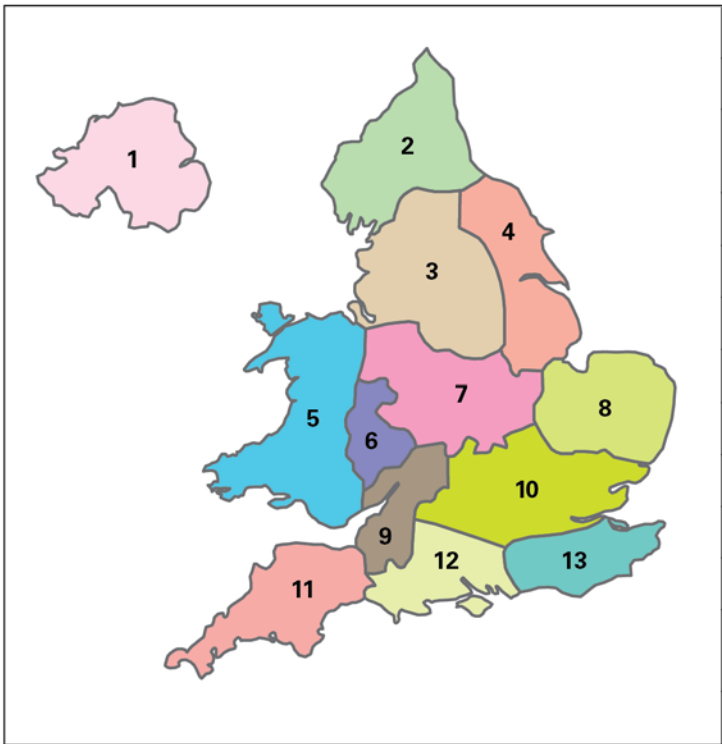
Principal aquifer — a regionally important aquifer defined by the Environment Agency as layers of rock that have high intergranular and/or fracture permeability, meaning they usually provide a high level of water storage (Environment Agency, 2013).

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 Central England region (Figure 1).



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

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

2 Background

2.1 NATIONAL GEOLOGICAL SCREENING GUIDANCE

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

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

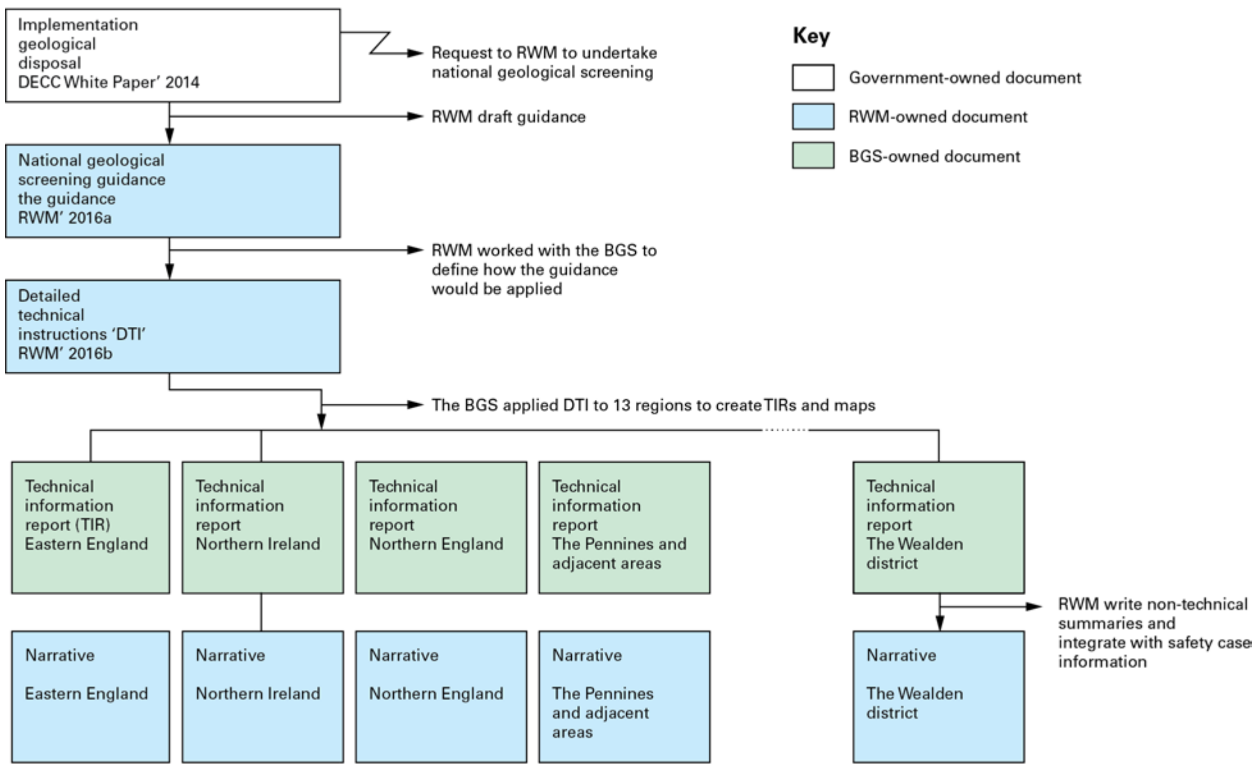


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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

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

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

2.2 DETAILED TECHNICAL INSTRUCTIONS

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

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

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

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

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

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

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

i. **Rock type**

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

ii. **Rock structure**

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

iii. **Groundwater**

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

iv. **Natural processes**

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

v. **Resources**

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

3 The Central England region

The Central England region comprises the counties of Warwickshire, Leicestershire, Rutland and the West Midlands, and parts of Cheshire, Shropshire, Staffordshire, Derbyshire, Nottinghamshire, Lincolnshire, Cambridgeshire, Northamptonshire and Worcestershire, and covers land between Chester, Nottingham, Northampton, Stratford-upon-Avon and Telford (Figure 3).

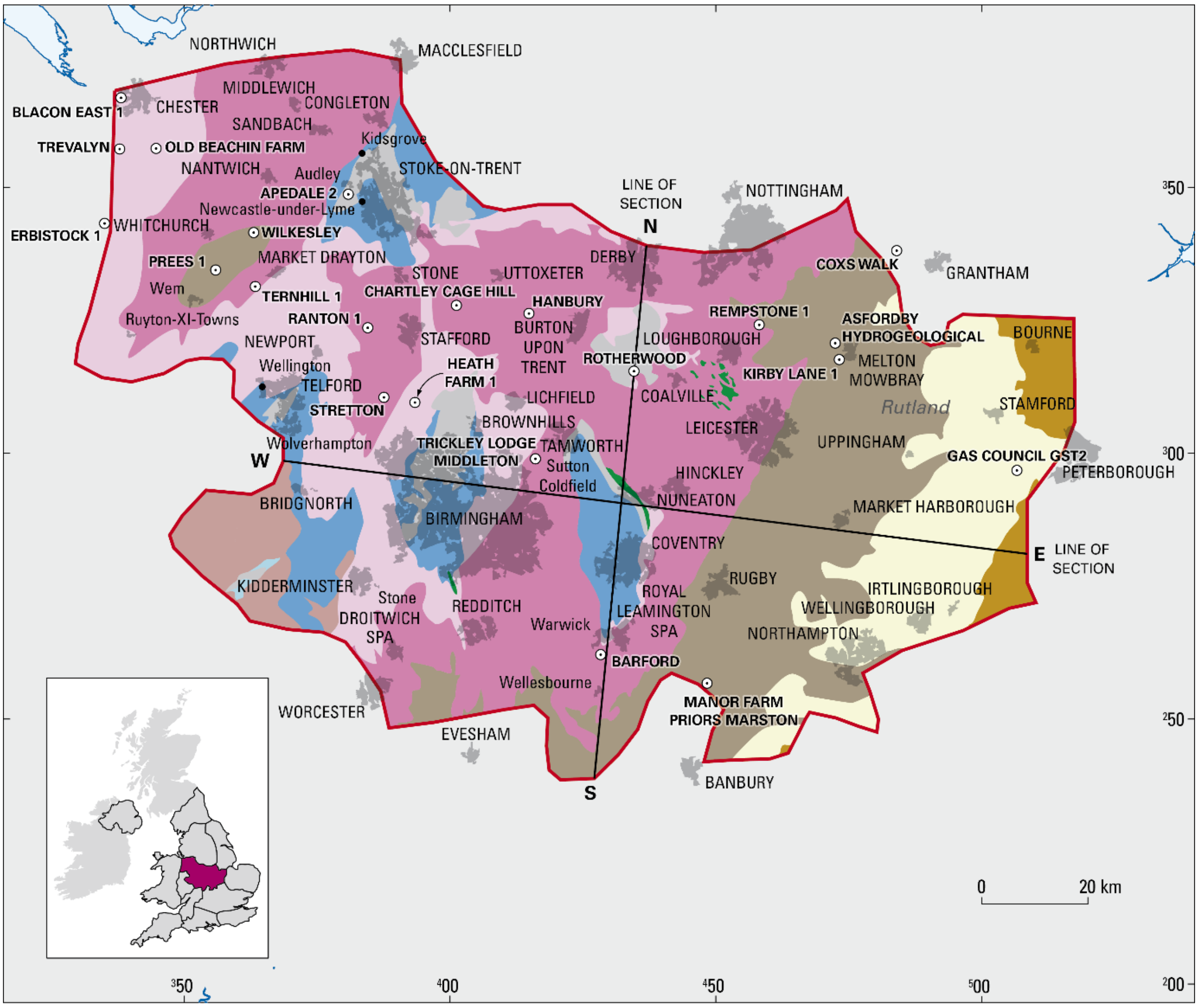
The region's landscape reflects the varied underlying bedrock geology, comprising gently undulating mudstone plains in much of the eastern and central parts and in Cheshire, with ridges of harder sandstone and limestone. Coalfields, including north Staffordshire, Coalbrookdale, Warwickshire, Leicestershire, south Derbyshire, Cannock and Clee, are present in the region, and are typified by an undulating landscape of valleys and low hills. Areas of rural upland are present in several localities, including Charnwood in Leicestershire and the Clee Hills in Shropshire (Figure 3).

The region's geology is well known from geological and geophysical surveys. At the surface, the rocks are often exposed in natural outcrops and quarries, whilst at depth our knowledge comes from mine plans and boreholes, many of the latter drilled for mineral resources, fossil fuels and groundwater. Over 150 boreholes in the region reach a depth of 1000 m or more; further evidence of the deeper geology and structures is provided by the interpretation of a limited number of seismic refection lines (Whittaker, 1985) and UK regional gravity and magnetic data. However, the information on the deeper rocks is mostly clustered in areas where there has been exploration for groundwater, coal, hydrocarbons and mineral salts (evaporites). Consequently, our understanding of the geology of the region is better in some areas than others and, in general, our understanding is poorer at depth.

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.

Geologically, the region is mainly underlain at shallow depths by sedimentary rocks (Figure 3). The youngest comprise a sequence of Jurassic, gently dipping and poorly cemented clays, sandstones and limestones, cropping out between Grantham and Evesham. The Cheshire and Shropshire area is underlain by a thick accumulation of Permo-Triassic sandstone and mudstone with interbedded rock-salt (halite). The central part of the region comprises thick accumulations of Permian and Triassic rocks, similar to those in Cheshire and Shropshire, in a series of linked sedimentary basins (Stafford, Worcester, Needwood, Knowle and the East Midlands shelf) with intrabasin highs where older rocks of Carboniferous to Precambrian age come to the surface. Some of the oldest rocks in England are present at Charnwood. These include volcanic tuffs, sandstone and mudstone and are up to 600 million years old.



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Age (Ma)	Map/section descriptor	Geological sub-units		Text descriptor
150–200	Jurassic sedimentary rocks	Ancholme Group: Kellaways Formation, Oxford Clay Formation		Younger sedimentary rocks
		Inferior and Great Oolite groups		
		Lias Group		
200–300	Permo-Triassic sedimentary rocks	Mercia Mudstone Group		
		Sherwood Sandstone Group		
300–360	Carboniferous sedimentary rocks	Warwickshire Group		Older sedimentary rocks
		Coal Measures Group		
		Mid and early Carboniferous rocks		
360–415	Devonian sedimentary rocks			
415–630	Early Palaeozoic to Precambrian	Various 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 Central England 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 Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

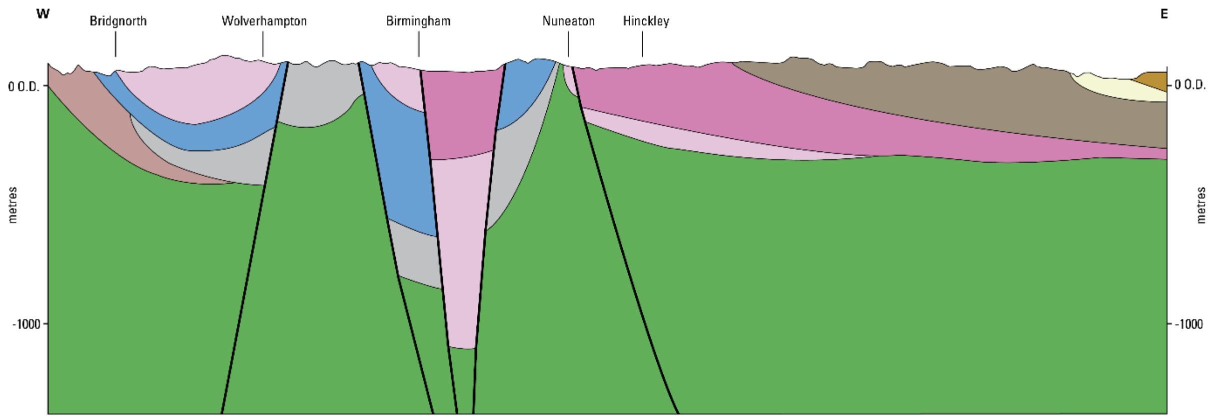


Figure 4 Schematic west to east cross-section through the Central England region. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

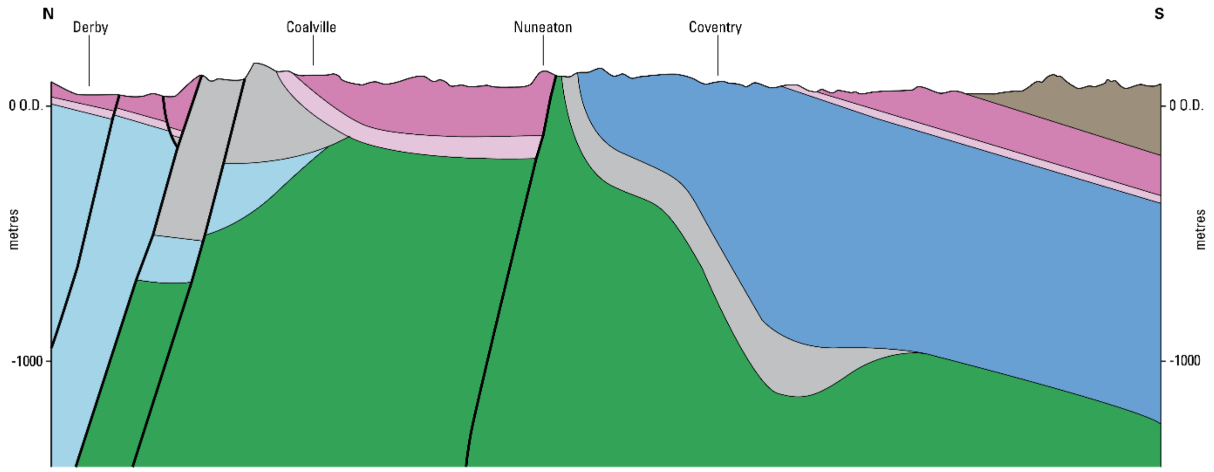


Figure 5 Schematic north to south cross-section through the Central England region. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

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 CENTRAL ENGLAND REGION

Table 3 presents a generalised vertical section (GVS) for the Central England region identifying the PRTIs that occur between 200 and 100 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 Central England region, the GVS groups the rocks of the UK into three age ranges: younger sedimentary rocks (Jurassic, Triassic, Permian); older sedimentary rocks (Carboniferous and Devonian), and basement rocks (Silurian and older) (Table 3, Column 1). Some of the rock units are considered to represent PRTIs present within the depth range of interest, between 200 and 1000 m below NGS datum. These include a number of lower strength sedimentary rocks units (LSSR), as well as evaporite (EVAP) and higher strength rock (HSR) units.

The undivided Kellaways and Oxford Clay formations are not considered to extend to depths suitable for them to be PRTIs in this region and hence are not discussed further. With the exception of small areas of Wenlock, Llandovery and Caradoc rocks in the extreme west, early Palaeozoic rocks comprising undivided Devonian rocks, Llandovery rocks, Silurian rocks, Caradoc rocks, Llanvirn rocks, Ordovician rocks and Cambrian rocks occur outside established cleavage belts (Acadian and Variscan) of Wales, the Lake District and south-west England and it is not known whether the mudstone component of these rocks preserves a pervasive cleavage, and therefore are sufficiently compacted and metamorphosed (see Table 2). Consequently they are not considered to be PRTIs and are not considered further. Ordovician felsic lava only occurs deeper than the depth range of interest and is also not discussed further. The Cumbrian Coast Group, a small area of which occurs in the north-east of the region, is sandstone dominated in this region and is therefore not considered a PRTI.

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 Central England (Hains and Horton, 1969) 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.

Three maps showing the regional distribution of PRTIs between 200 to 1000 m below NGS datum for the three generic host rock types are provided in Figures 6, 7 and 8. A summary map showing the combined lateral extent of all PRTIs is provided in Figure 9.

Table 3 Schematic GVS for the Central England region showing units that contain PRTIs and/or principal aquifers. Geological units are generally shown in stratigraphical order and display variable levels of resolution reflecting the resolution within the UK3D model. The units are not to vertical scale and due to regional variations; some units may be locally absent or may be recognised in different stratigraphical positions from those shown. See Figures 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	Jurassic	Kellaways and Oxford Clay formations	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Great Oolite and Inferior Oolite groups	Sandstone, limestone and argillaceous rocks	N/A	N/A	N/A	Great Oolite and Inferior Oolite groups
		Lias Group	Mudstone, siltstone, limestone and sandstone	N/A	Lias Group	N/A	N/A
	Triassic	Mercia Mudstone Group (including Penarth Group in UK3D)	Mudstone with local siltstone and evaporite deposits of anhydrite, gypsum and halite	N/A	Mercia Mudstone Group including Penarth Group	Wilkesley Halite Member; Northwich Halite Member	Marginal facies (conglomerate and breccia) of Mercia Mudstone Group
		Sherwood Sandstone Group	Predominately red sandstone, siltstone and mudstone	N/A	N/A	N/A	Sherwood Sandstone Group incorporating the Lenton Sandstone in UK3D; the Helsby Sandstone, Wilmslow Sandstone and Chester formations
	Permian	Cumbrian Coast Group	Mudstone, siltstone and sandstone with evaporites including halite	N/A	N/A	N/A	N/A
		Appleby Group	Sandstone and conglomerate	N/A	N/A	N/A	Collyhurst Sandstone Formation
		New Red Sandstone Supergroup (various sandstone formations)	Sandstone	N/A	N/A	N/A	Bridgnorth Sandstone Formation
		Zechstein Group	Dolomite, limestone, evaporite, mudstone and siltstone	N/A	N/A	N/A	Cadeby Formation
OLDER SEDIMENTARY ROCKS	Carboniferous	Warwickshire Group	Siltstone and sandstone with subordinate mudstone; mudstone, siltstone, sandstone, coal, ironstone and ferricrete	N/A	Warwickshire Group	N/A	Allesley, Whitacre, Keresley members of the Salop Formation
		Pennine Coal Measures Group	Mudstone, siltstone, sandstone, coal and ironstone	N/A	N/A	N/A	N/A
		Millstone Grit Group	Sandstone, siltstone and mudstone	N/A	N/A	N/A	N/A
		Craven Group	Siliciclastic to calcareous mudstone and limestone	N/A	N/A	N/A	N/A
		Unnamed extrusive rocks Tournaisian–Visean	Felsic lava and felsic tuff	Unnamed extrusive rocks Tournaisian–Visean felsic lava and felsic tuff	N/A	N/A	N/A
		Tournaisian–Visean = Carboniferous Limestone Supergroup	Limestone, with minor sandstones	N/A	N/A	N/A	Carboniferous Limestone Supergroup
	Devonian	Devonian rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
BASEMENT ROCKS	Silurian	Pridoli rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Ludlow rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Wenlock rocks (undivided)	Mudstone, siltstone and sandstone	Wenlock rocks	N/A	N/A	N/A
		Llandovery rocks (undivided)	Mudstone, siltstone and sandstone	Llandovery rocks	N/A	N/A	N/A
	Ordovician	Caradoc rocks (undivided)	Mudstone, siltstone and sandstone	Caradoc rocks	N/A	N/A	N/A
		Llanvirn rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Arenig rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Tremadoc rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Ordovician volcanic rocks and sills	Tuff	N/A	N/A	N/A	N/A

BASEMENT ROCKS	Cambrian	Cambrian rocks	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Intrusive igneous rocks	Granite, foliated	Intrusive igneous rocks	N/A	N/A	N/A
		Unnamed igneous intrusion, Cambrian to Ordovician	Felsic rock	Melton Mowbray granodiorite	N/A	N/A	N/A
	Precambrian	Avalonian Proterozoic and Neoproterozoic rocks (undivided)	Varied lithologies	Neoprotero-zoic rocks	N/A	N/A	N/A
		Charnian Supergroup	Volcanoclastic rocks	Charnian Supergroup	N/A	N/A	N/A

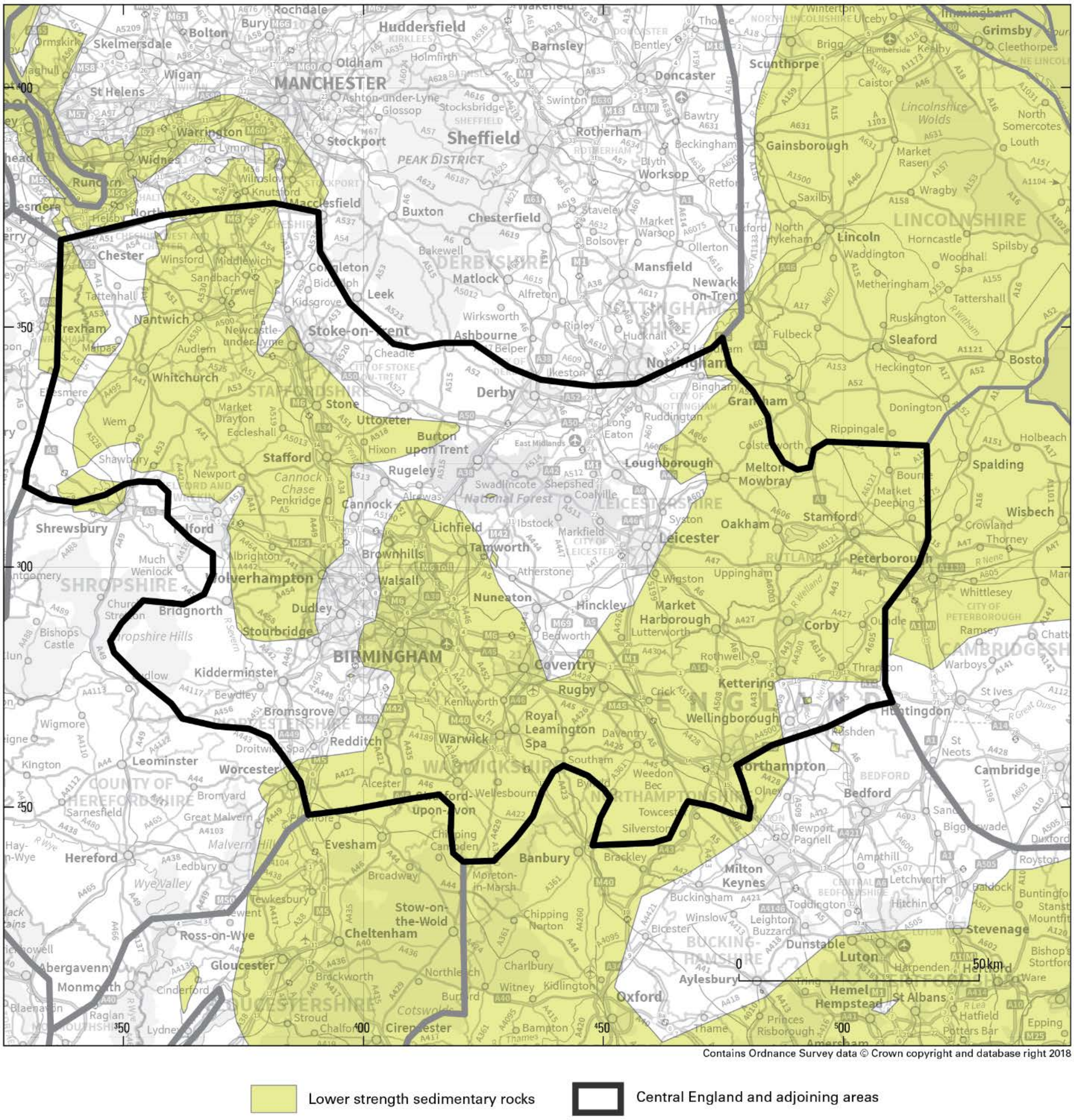


Figure 6 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Central England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI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

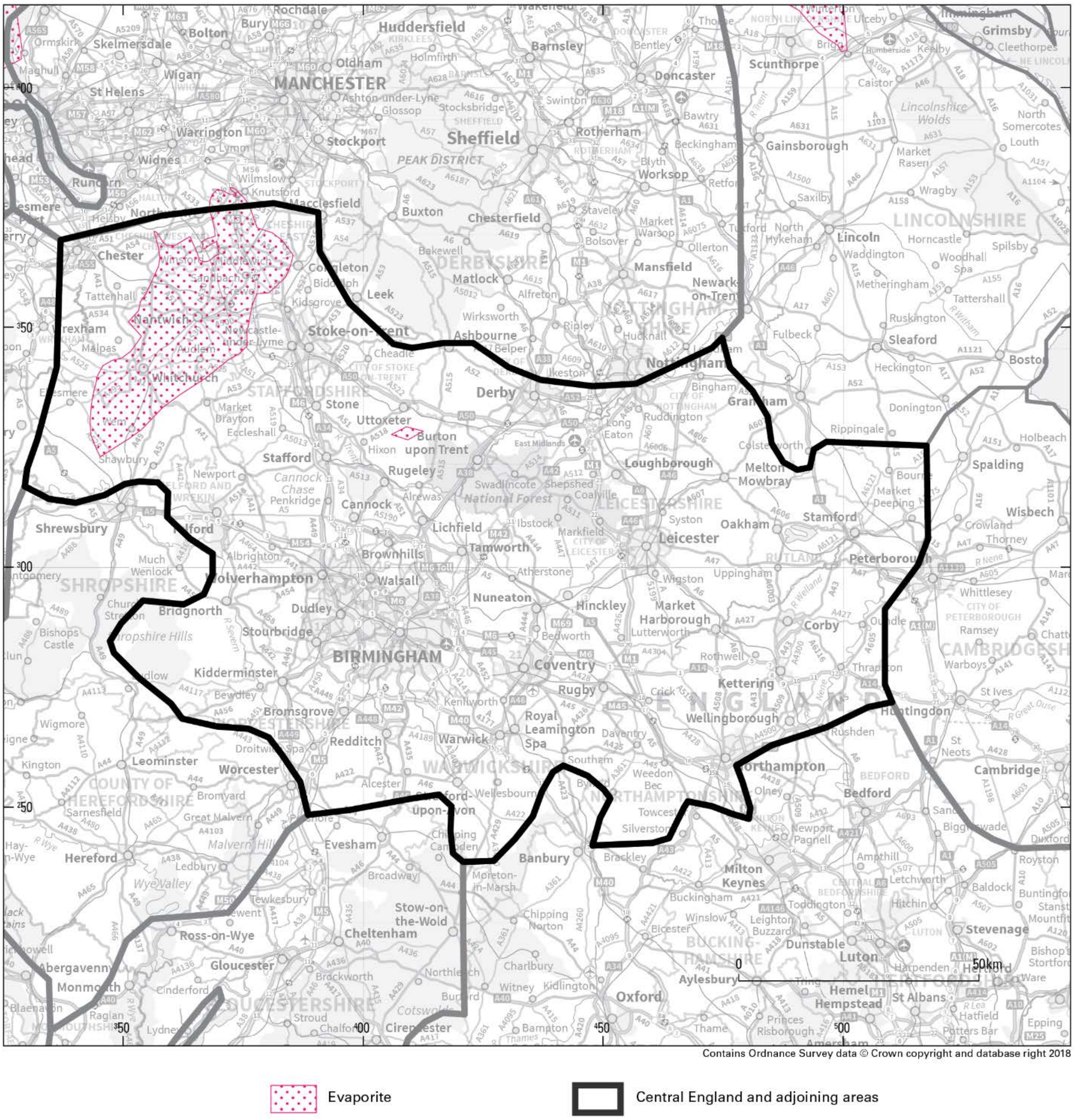


Figure 7 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the Central England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI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

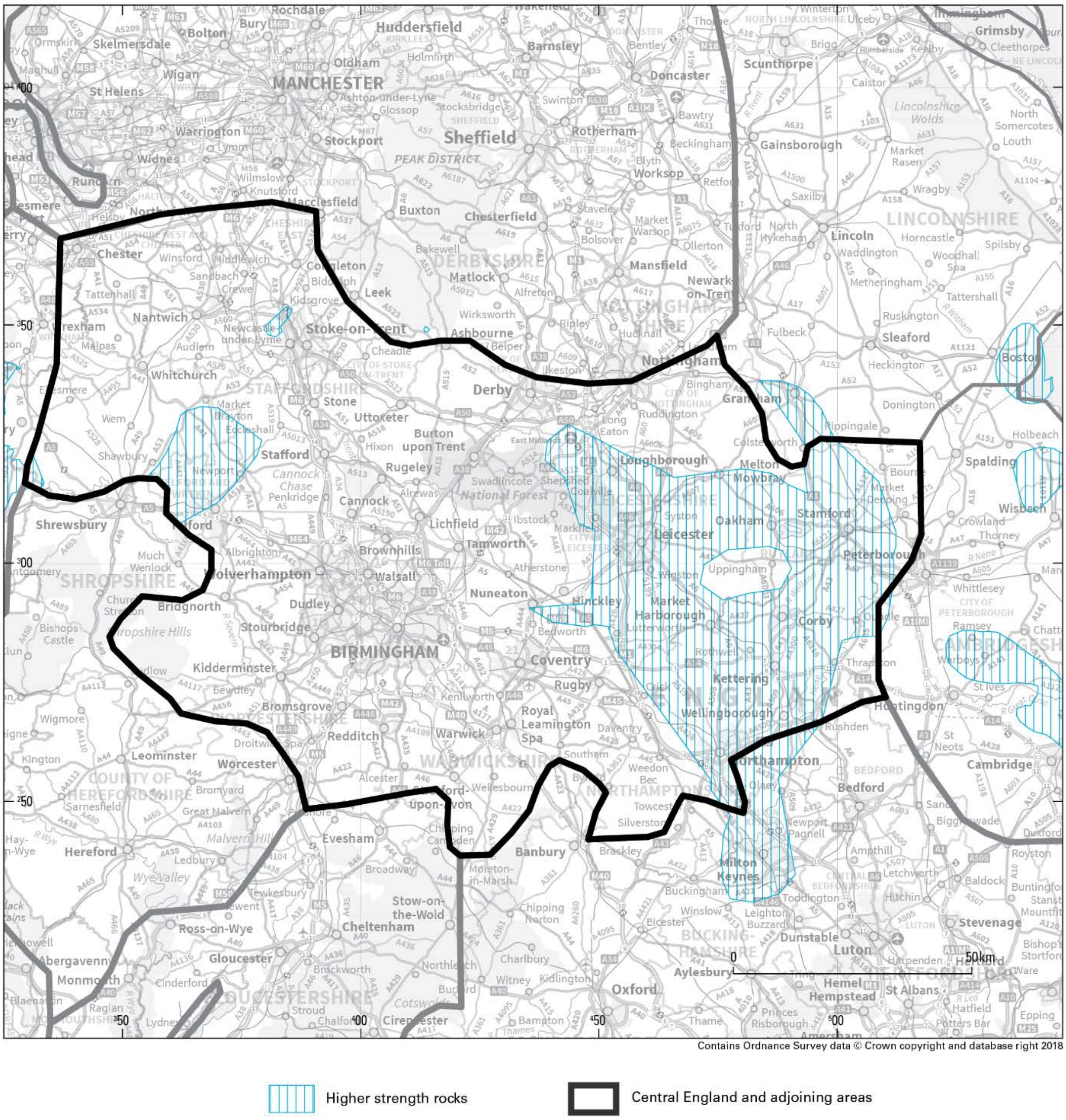


Figure 8 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Central England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI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

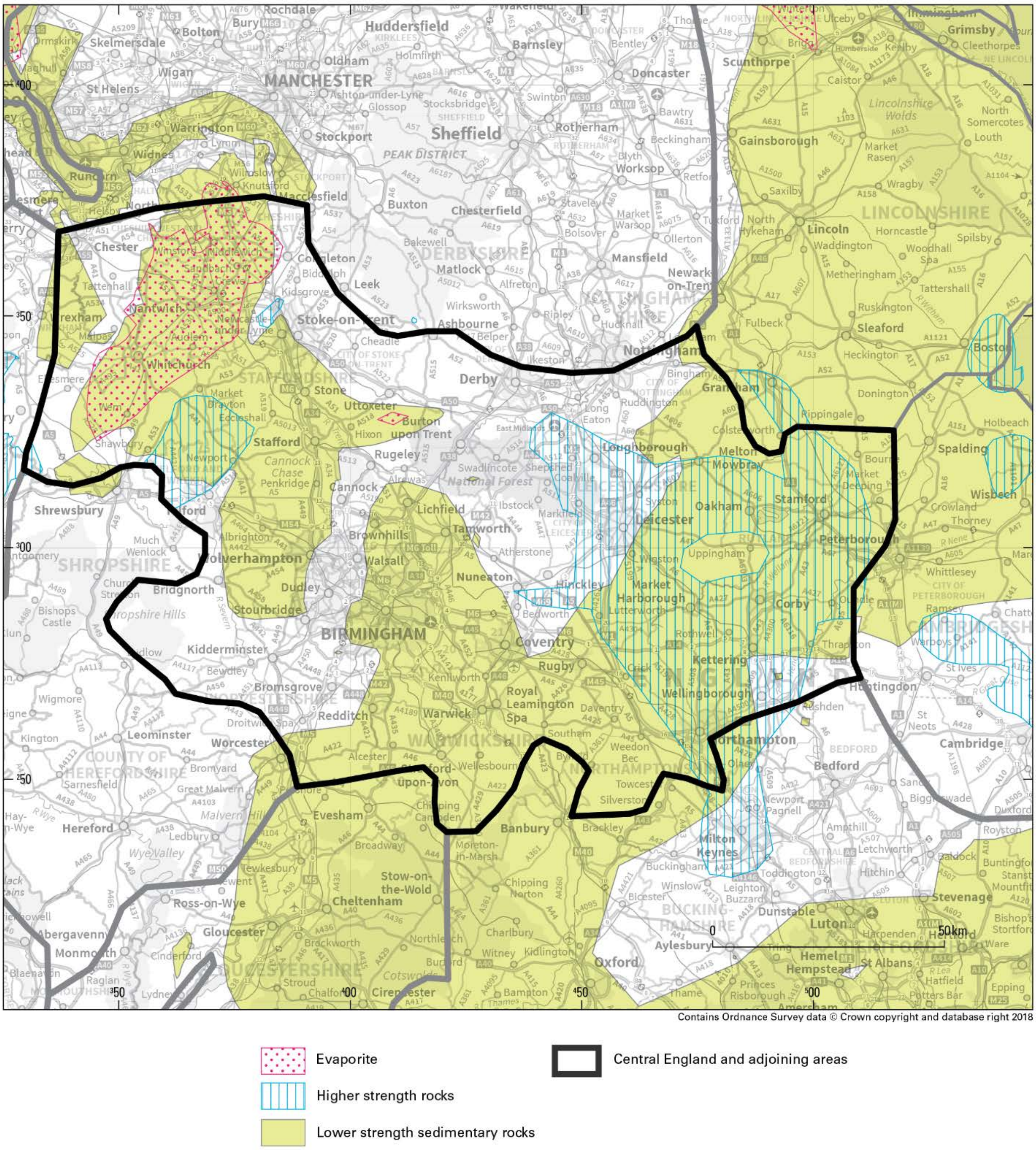


Figure 9 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Central England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey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

4.2.1 Younger sedimentary rocks

4.2.1.1 Lias Group – LSSR

The Early Jurassic Lias Group is present at outcrop between Grantham (Lincolnshire) and Royal Leamington Spa (Warwickshire). In response to a prevailing dip of about a degree to the south-east, the unit becomes deeper towards the south-east, where it is overlain by younger Jurassic rocks (Inferior and Great Oolite, and

Ancholme groups); it is inferred to lie within the depth range of interest in the area around Melton Mowbray (Leicestershire) and Stamford (Lincolnshire) to Wellingborough (Northamptonshire), although there is no borehole evidence to prove this. In this area, it was deposited on the geological structure called the East Midlands shelf.

The Lias Group comprises an upper unit of siltstone/mudstone (the lower Dyrham Formation and upper Whitby Mudstone Formation), with an intervening regionally important marker bed, the ferruginous sandstone of the Marlstone Rock Formation; together, this interval is up to 74 m thick (Carney et al., 2009). This overlies the Charmouth Mudstone Formation, which is dominated by mudstone and subordinate limestone beds; this is up to 180 m thick (Carney et al., 2009). A lower unit, the Blue Lias Formation, consists of brown and grey mudstone with pale grey limestones, which is up to 120 m thick (Carney et al., 2009).

4.2.1.2 Undivided Mercia Mudstone Group and Penarth group — LSSR and EVAP

The Mercia Mudstone Group and overlying Penarth Group, both LSSR PRTIs are undivided in the NGS3D model.

The Mercia Mudstone Group (previously known as 'Keuper Marl') was deposited in several actively subsiding Permo-Triassic basins, half-graben and the intervening highs that developed in response to the breaking up of the Pangaea supercontinent (Hains and Horton, 1969; Howard et al., 2008). This structural setting has resulted in a variable thickness and composition for the unit across the area. A partial section of 1515 m was proved in the Wilkesley Borehole in Cheshire (see Figure 3)), with another partial section of 299 m proved in the Hanbury Borehole in Staffordshire (see Figure 3)); the unit is 198 m thick in Leicestershire (Hains and Horton, 1969). The unit has typically gentle dips of less than 5 degrees, with azimuths varying in response to the local structural setting, although in the eastern part of the region, dips are about a degree to the south-east.

The unit has been proved by numerous boreholes drilled to explore for coal and hydrocarbons in the underlying rocks, and also to prove or exploit evaporate beds from within the unit, including halite in Cheshire and gypsum in Staffordshire and Nottinghamshire. These boreholes constrain the top and base of the unit and also give information regarding the composition, which can be derived from core samples or downhole geophysical logs where available. Further information regarding the distribution of the Mercia Mudstone Group is provided by 2D seismic reflection data that was shot to help exploration for hydrocarbons. There is less confidence in the position of the top and base of the unit where borehole and seismic reflection data are sparse or absent.

The Mercia Mudstone Group is present at outcrop beneath much of Cheshire and the northern part of Shropshire (the Cheshire basin), to the north-west of the Wem–Red Rock fault system that defines the south-eastern limit of the Cheshire basin between Macclesfield (Cheshire) and Ruyton-XI-Towns (Shropshire) (Figure 10). Towards the northern and eastern parts of the Cheshire basin, south of Northwich, it is present within the depth range of interest, indicated by numerous boreholes drilled in the Holford brine field in north Cheshire (Figure 11).

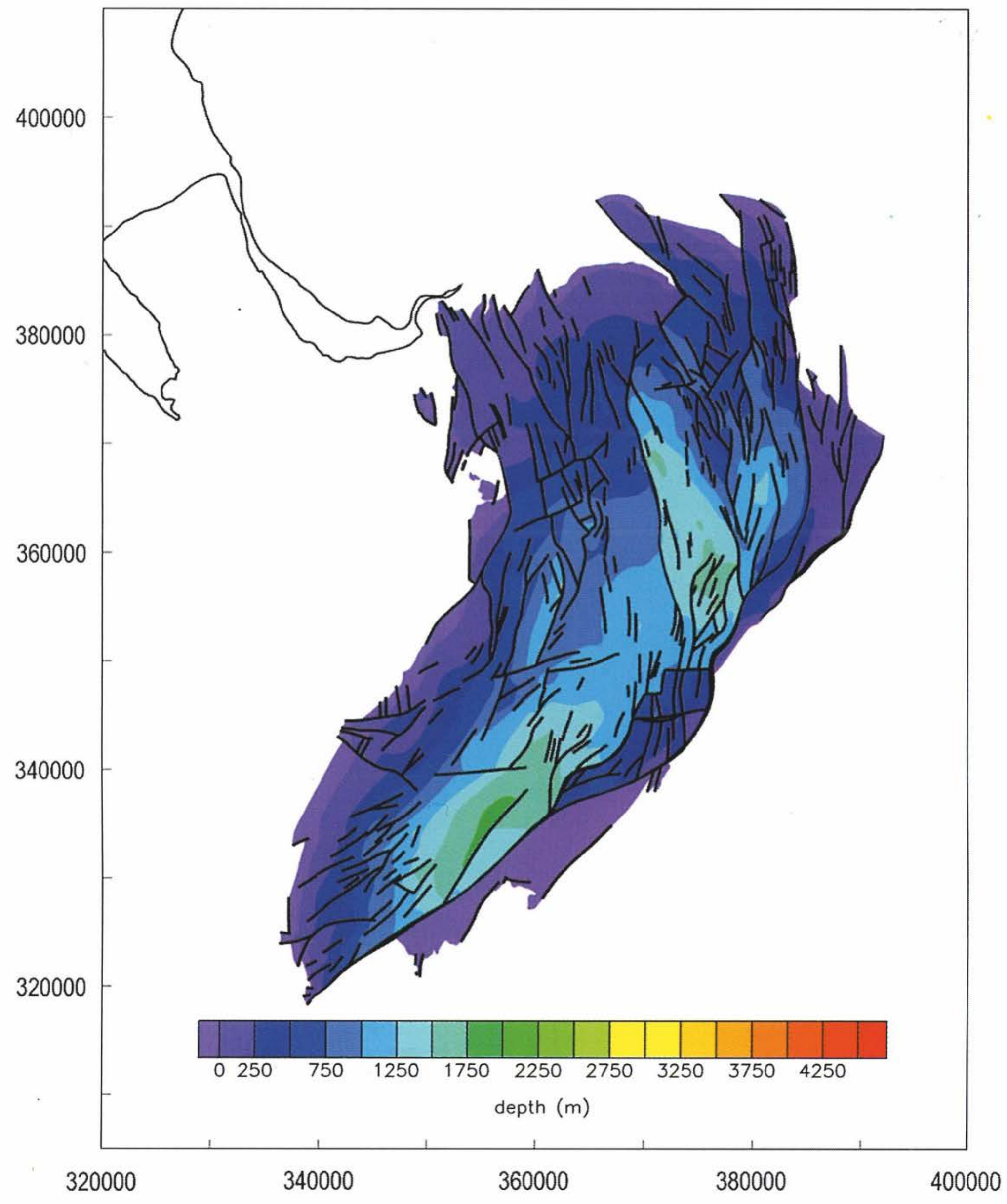


Figure 10. Depth contours on the base of the Mercia Mudstone Group across the Cheshire basin (from Plant et al., 1999). British Geological Survey © UKRI 2018.

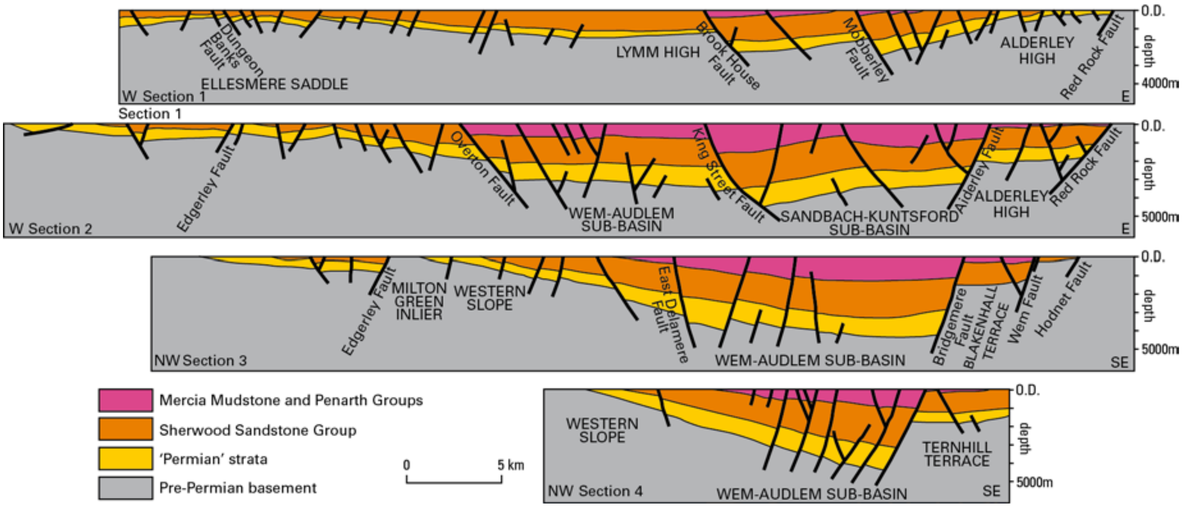


Figure 11 True-scale cross-sections through the Cheshire basin showing development of the Mercia Mudstone Group (from Plant et al., 1999); locations are given on fig. 37 from Plant et al. (1999). British Geological Survey © UKRI 2018.

The Mercia Mudstone Group is also present around Stafford (Stafford basin), constrained to the north by the Swinnerton Fault north of Stone (Staffordshire) and to the east by the Hopton and Brewood faults, between Stone and north-west of Wolverhampton in the West Midlands; it is thought to lie above the depth range of interest in this basin although there is no borehole data to support this assumption.

The unit occurs throughout much of the central part of Staffordshire across to Derbyshire (the Needwood basin), where it is present in the depth range of interest as indicated by the Chartley Cage Hill Borehole near Stafford, and Hanbury Borehole, near Burton upon Trent, Staffordshire (Howard et al., 2008). See Figure 3 for the location of boreholes referred to in this section. The unit is also present through south Nottinghamshire and north-east Leicestershire (East Midlands shelf), where it is constrained to the west by its unconformable boundaries with the Sherwood Sandstone Group and the Charnian Supergroup. In the extreme eastern part of this area, the unit is over 200 m in depth (e.g. Rempstone 1 Borehole). The Mercia Mudstone Group is also present, though above the depth range of interest, in the southern part of the area, including the eastern part of the West Midlands between the Birmingham and Western Boundary faults, and in the northern part of Warwickshire and north-east Worcestershire, between Warwick, Birmingham (West Midlands) and Redditch (Knowle and Worcester basins). It is also present under a cover of younger rocks, and within the depth range of interest, near Whitchurch (Shropshire) (as proved by the Prees 1 Borehole (Evans et al., 1993), and in the eastern part of the area, to the east of Grantham to Royal Leamington Spa (e.g., Asfordby Hydrogeological Borehole, (Howard et al., 2008)), and also to the south of Warwick and Redditch (e.g., as proven by the Manor Farm Priors Marston Borehole).

The Mercia Mudstone Group comprises red and green-grey mudstone and siltstone; rare beds of mostly very fine-grained sandstone comprise about 10 per cent of the succession (Howard et al., 2008). In the northern part of this region, southwards to Tamworth, the lower part of the Mercia Mudstone Group, reaching a maximum thickness of about 150 m near Chester (Earp and Taylor, 1986), is a distinct siltstone unit called the Tarporley Siltstone Formation. Where it has been identified, the Tarporley Siltstone has been excluded from the Mercia Mudstone Group PRTI due to the high silt content.

Significant accumulations of halite (rock-salt) are present as two members in the middle part of the Mercia Mudstone Group (Sidmouth Mudstone Formation) in the Cheshire basin: the upper Wilkesley and lower Northwich halites, separated by 305 to 610 m of mudstone (Hains and Horton, 1969). The Wilkesley Halite Member is 404 m thick in the Wilkesley Borehole and about 350 m thick in the Prees 1 Borehole (Plant et al., 1999). The Northwich Halite Member has been dry mined and solution mined beneath parts of north Cheshire. The halite beds are near surface under superficial deposits, or beneath solution and collapse breccias (so-called 'wet rockhead') between Northwich (Cheshire) and Ruyton-XI-Towns (Shropshire), and around Sandbach and Nantwich (Cheshire) (Wilson, 1993). The beds of halite dip towards the south and east, towards the central part of the Cheshire basin near Whitchurch (Wilson, 1993); the Northwich Halite Member thickens to over 275 m to the north-east of Middlewich, Cheshire (Figure 12).

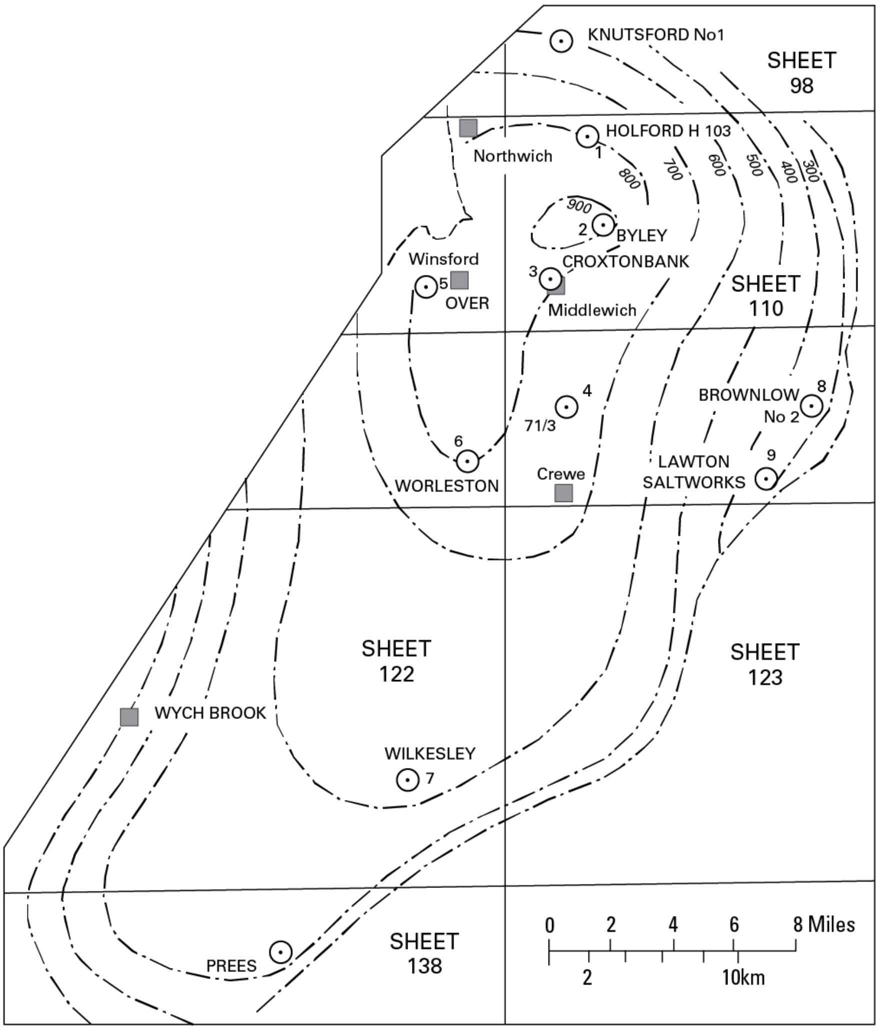


Figure 12 Thickness (in feet) of the Northwich Halite Member of the Mercia Mudstone Group across the central part of the Cheshire basin (from Plant et al., 1999). British Geological Survey © UKRI 2018.

These halite members comprises crystalline and structureless accumulations of halite that locally exceed 30 m, which are interbedded with subordinate but regionally extensive beds of mudstone, typically less than 9 m thick (Earp and Taylor, 1986). Thinner beds of halite have also been mapped around Stafford although their distribution is largely conjectural due to the paucity of borehole information. Halite has also been worked near Uttoxeter and Weston-on-Trent in Staffordshire (Hains and Horton, 1969), but its distribution is likewise not well constrained by subsurface data.

The Late Triassic Penarth Group, overlying the Mercia Mudstone Group (previously known as the Rhaetic Beds) was deposited in a shallow marine setting subject to episodic lagoonal and estuarinal conditions. The Penarth Group is present at the surface across the central and western parts of the region but only attains into the depth range interest to be considered a PRTI in the east of the region, west of Melton Mowbray. In the western part of the region, the Penarth Group includes the Westbury Formation and the younger Lilstock Formation. These formations are characterised by dark-grey mudstones with subordinate limestones, sandstones and fossiliferous sandy units known as ‘bone beds’ and grey to grey-green siltstones and shales respectively. The Melton Spinney Borehole near Melton Mowbray see Figure 3) proves a thickness for the Penarth Group of about 9 m at a drilled depth of 273.5 m below the surface.

4.2.2 Older sedimentary rocks

4.2.2.1 WARWICKSHIRE GROUP — LSSR

The Warwickshire Group comprises a diverse assortment of mudstones, sandstones and limestones encompassing Carboniferous strata (typified by poor developments of coal beds) that are Westphalian C–D and Stephanian in age, formerly termed 'Barren Measures' (Powell et al., 2000; Waters et al., 2009). The Warwickshire Group is present in the Warwickshire, south Staffordshire, north Staffordshire, Wyre Forest, Coalbrookdale, Shrewsbury and Denbighshire coalfields in this area; in addition to these regions, it is also present under large parts of the intervening areas, but is restricted to the area west of Royal Leamington Spa and Nuneaton (Warwickshire). Due to the complex Carboniferous basin evolution and phases of subsequent basin inversion, the unit is highly variable in thickness and present at a variety of depths across the area (Figures 13 and 14).

This account focuses on where the unit is mapped on the NGS3D sections as being within the depth range of interest. Borehole locations are shown on Figure 3.

The unit is present within the depth range of interest between Chester and Northwich; it has not been proved by boreholes but is assumed to be present based on deep borehole penetrations from nearby areas (e.g., Old Beachin Farm Borehole; Earp and Taylor, 1986). In this district, the unit comprises a cyclic development, up to 900 m thick, of red and purple mudstone with subordinate siltstone and about 10 per cent sandstone (Earp and Taylor, 1986).

Between Chester and Malpas (Cheshire), the unit has been proved in several deep exploration boreholes including 29 m at Blacon East 1, 702 m at Erbistock 1 and 978 m at Trevalyn. In this district, the unit dips broadly eastwards, with several faults including the Llanelidan and Edgerley faults maintaining the unit at levels within the depth range of interest. Based on borehole provings, the unit comprises red and brown mudstone with up to 20 per cent sandstone and rare beds of coal in the middle part.

Near Audley (Staffordshire), the unit is present in the south-eastern part of the Cheshire basin within the depth range of interest. Its position here is inferred based on outcrop of the unit to the south-east and an assumed dip to the north-west. The unit is up to 1460 m thick, and comprises red-brown, grey and green mudstone with beds of sandstone and limestone in the upper two thirds of the succession; limestone and sandstone account for 10 per cent of the unit as a whole (Rees and Wilson, 1998).

In the Stoke-on-Trent area (Staffordshire), the unit is present within the depth range of interest, with the southern limit defined by the Swinnerton Fault. The unit is known to be present at outcrop, and is thought to extend to over 350 m below NGS datum based on the thickness of the unit proved in the Stoke area. The composition is likely to be similar to that in the Audley district.

An extensive development of the unit within the depth range of interest is present between Market Drayton (Staffordshire), Stafford and Bridgnorth (Shropshire). The Wem Fault in the north defines its limits; to the south-east of this, the unit thins over the north-western part of the Church Stretton fault structure (near Telford in Shropshire). Further south and east, the unit is present to the Bushbury Fault, near Stafford. South of this, the unit is present in depth range of interest between Telford (defined by the Lightmoor Fault) across to Wolverhampton, beneath the Stafford basin. The unit is proved by several deep boreholes including about 340 m at Stretton (Bridge and Hough, 2002), 180 m at Ternhill 1, 173 m at Ranton 1 and 305 m at Heath Farm 1, which gives confidence to the subsurface distribution. The unit in this district is described as an upper part comprising up to 424 m of mudstone and sandstone (up to 30 per cent) resting on up to 175 m of sandstone with about 20 per cent mudstone, coal and limestone, overlying a lower part of up to 130 m of variegated mudstone with about 10 per cent pebbly sandstone (Bridge and Hough, 2002).

South of Birmingham, the unit is present within the depth range of interest to the north-west of the Birmingham Fault, northwards to Lichfield, where the unit thins onto the southern part of the concealed Pennine block. To the east of this, the unit is present from Brownhills in the West Midlands eastwards, where the unit thins to the east of Sutton Coldfield, before thickening again across the Warwickshire coalfield near Nuneaton, where it reaches 1225 m in thickness (Waters et al., 2009). The unit is present to the south of this point towards Banbury. The unit is again proved by several deep boreholes which add confidence to its distribution and composition. These include 239 m at Trickley Lodge, Middleton and 1083 m at Barford. In the Coventry area, the unit is described as an interbedded succession of mudstone with about 20 per cent of sandstone, coal and limestone (Bridge et al., 1998).

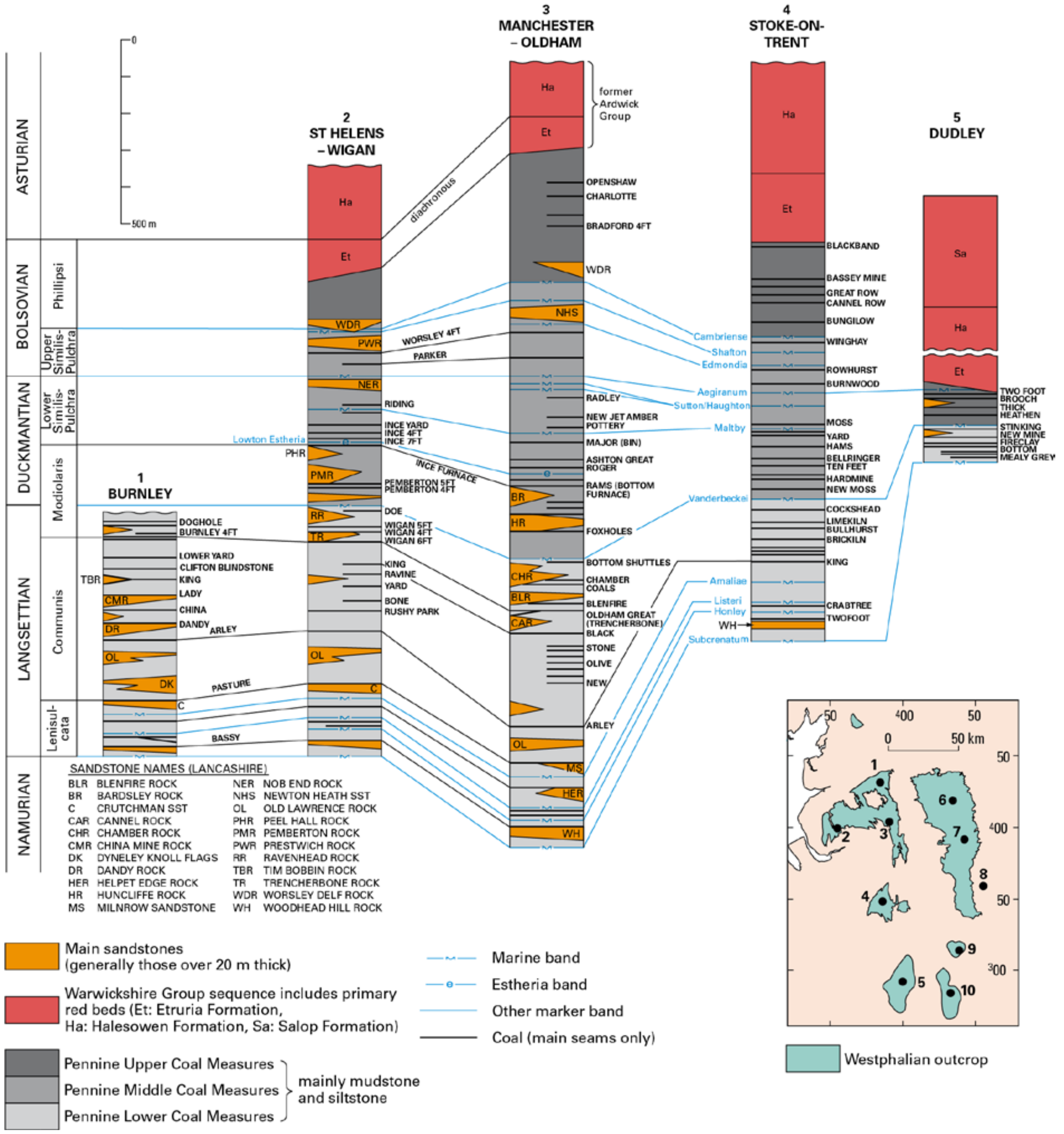


Figure 13 Generalised sections of the Pennine Coal Measures Group from Lancashire to South Staffordshire demonstrating thickness variations within the Warwickshire Group (from Waters et al., 2009). British Geological Survey © UKRI 2018.

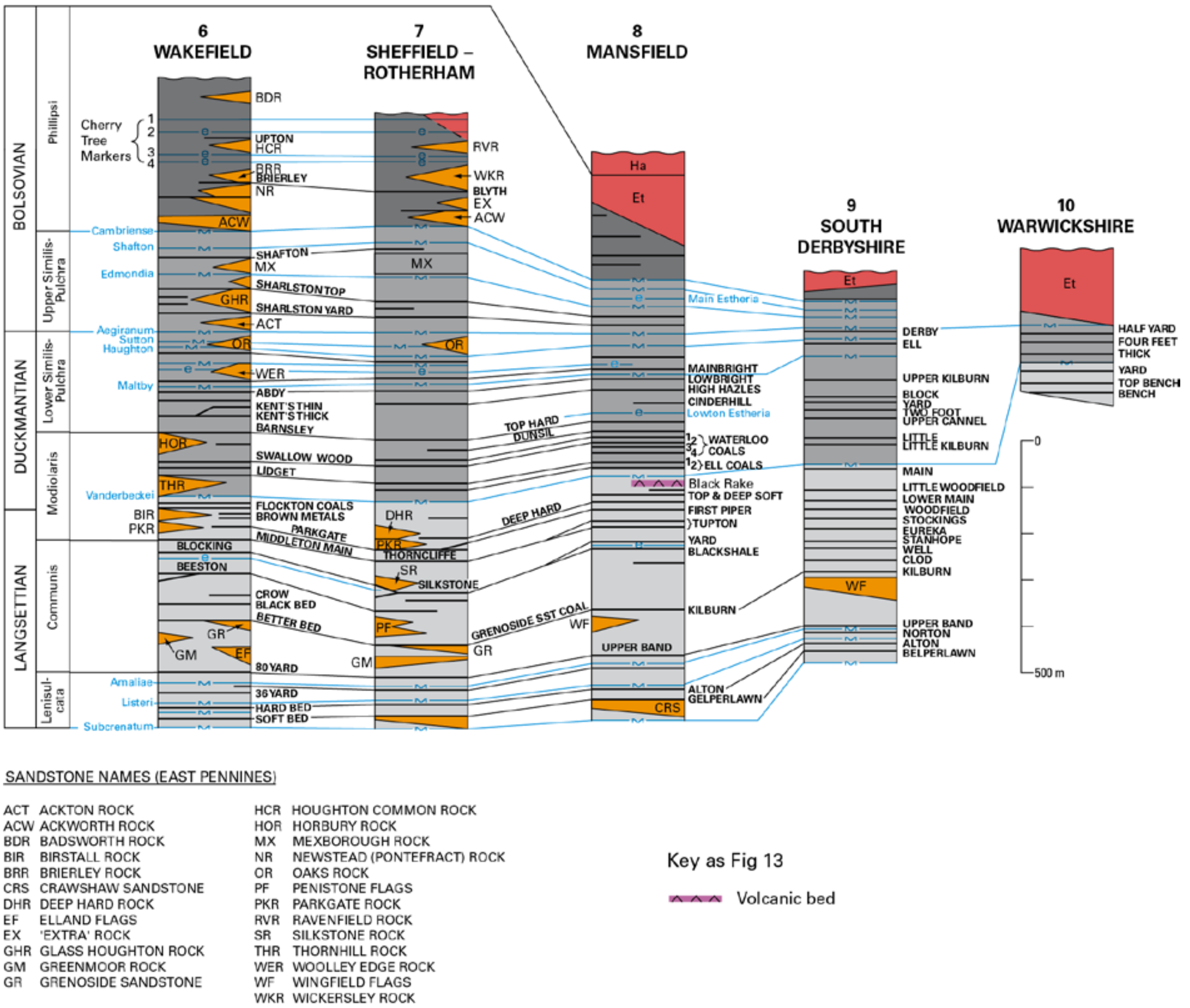


Figure 14 Generalised sections of the Pennine Coal Measures Group from the east Pennines to the Warwickshire coalfields demonstrating thickness variations within the Warwickshire Group (from Waters et al., 2009). British Geological Survey © UKRI 2018.

4.2.2.2 Unnamed Extrusive Rocks, Tournaisian–Visean– HSR

This unit is present, partly within the depth range of interest, between Stoke-on-Trent and Kidsgrove (Staffordshire). The unit was proved by the Apedale 2 Borehole (see Figure 3), which drilled 847 m (base not proved) of felsic tuff from a depth of 462 m. The tuff has a geochemical profile that suggests a Tournaisian–Visean affinity (Rees and Wilson, 1998). The lateral extent of this unit is uncertain due to the lack of other evidence, including geophysical, describing the distribution away from the Apedale 2 Borehole.

4.2.3 Basement rocks

4.2.3.1 Undivided Wenlock, Llandovery and Caradoc Rocks — HSR

These rocks occur as a small area within the extreme west of the region, south of Oswestry and adjacent to the main development of these rocks within the Wales region. They comprise mudstone-dominated units, which locally occur within the 'Acadian cleavage front' and have developed a slaty cleavage. To the east of the cleavage front these strata are not considered PRTIs. Details of these strata are provided in the corresponding report for the Wales region.

4.2.3.2 Intrusive igneous rocks — HSR

The distribution of unnamed intrusive igneous rocks (Ordovician) in the subsurface is not well known; it is thought that they are present in the subsurface in two areas within the region.

Near Loughborough (Leicestershire), and possibly within the depth range of interest, they have been shown on the NGS3D cross-sections between the Thringstone, Sileby and Normanton Hills/Hoton faults. Carney et al. (2001) indicates the presence of igneous rocks at depth in this area as the 'Diseworth Intrusion' (Figure 15) based on a positive magnetic anomaly in this area. The composition of this rock unit is not known.

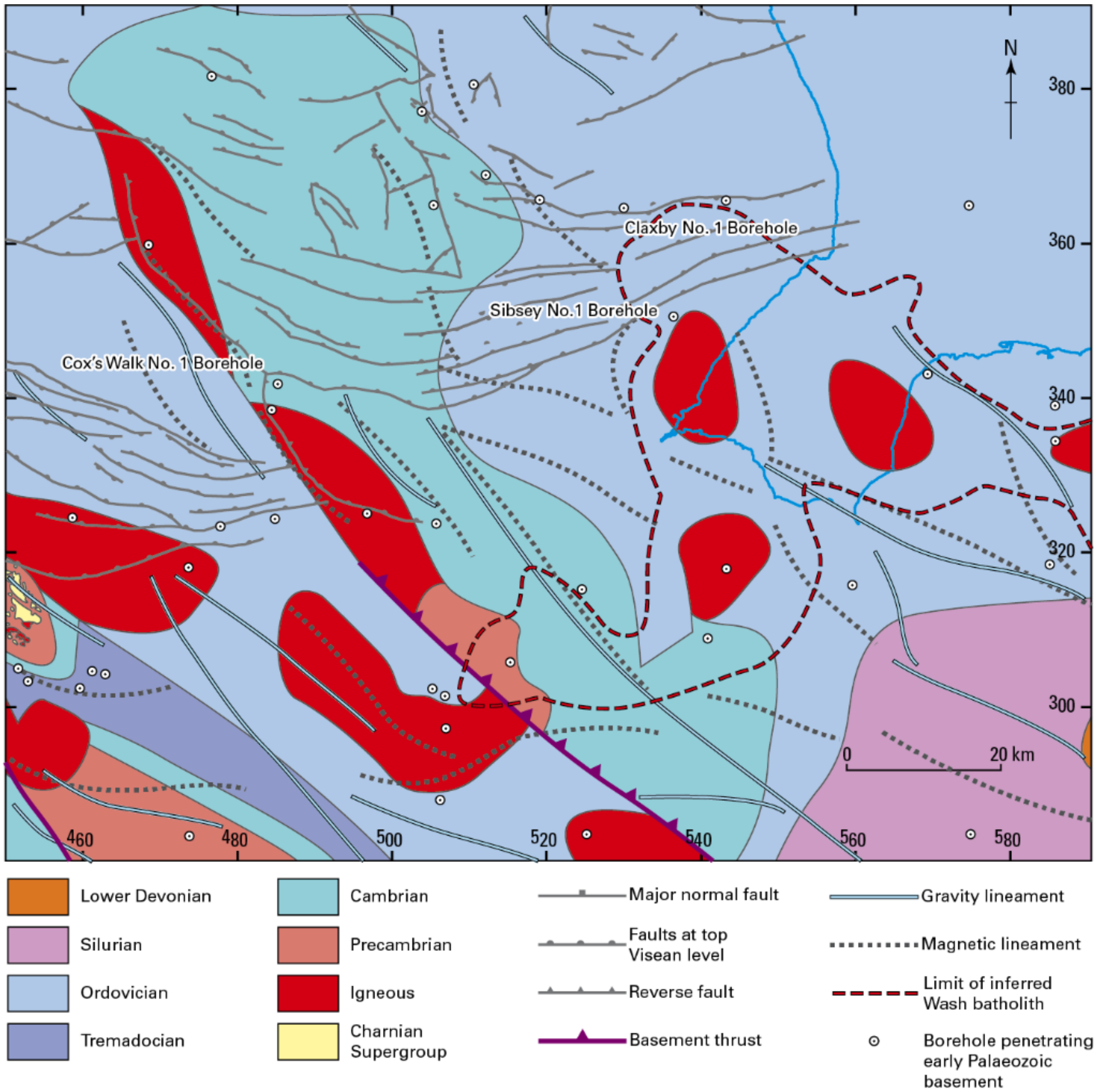


Figure 15 Map showing the information on the 'Caledonian' basement structure and lithology at depth based on geophysical and borehole data in the south of the region (from Pharaoh et al., 2011). The subsurface limit of the inferred Wash batholith is shown by the dashed red line. British Geological Survey © UKRI 2018.

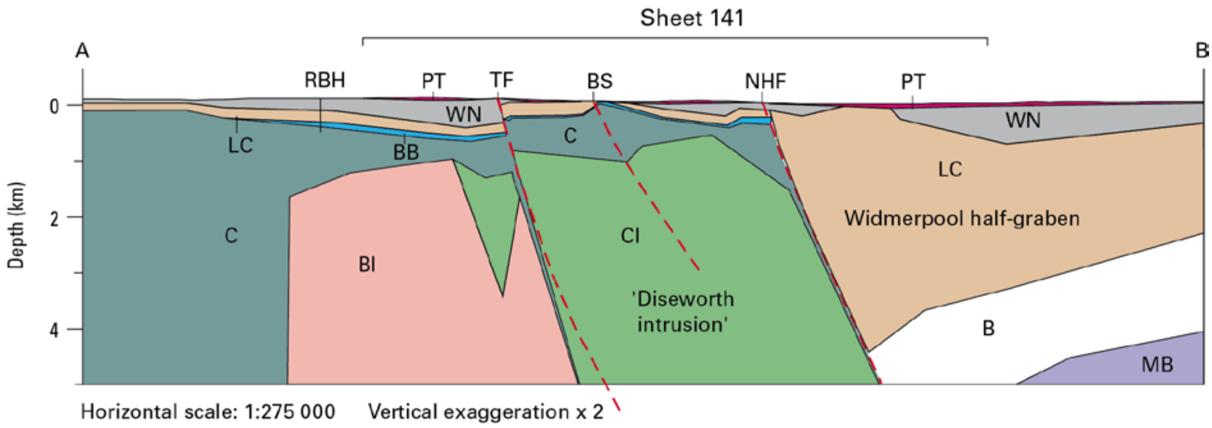


Figure 16 Distribution of unnamed intrusive igneous rocks (Ordovician) ('Diseworth Intrusion') near Loughborough (Carney et al., 2001). Abbreviations: NHF Normanton Hills Fault, TF Thringstone Fault, BS Breedon Structure, RBH Rotherwood Borehole, PT Permo-Triassic, WN Westphalian and Namurian, LC early Carboniferous, BB basal Carboniferous beds, C Cambrian, CI Caledonian(?) intrusions, B basement, BI high density basement, MB magnetic basement rocks. British Geological Survey © UKRI 2018.

The rocks are also shown within the depth range of interest to the east of an area approximately 10 km north-east of Oakham and midway between Corby and Peterborough (Figure 15 shows the western mapped limit). Their limits are indicated by regional magnetic geophysical data (Carney et al., 2009; Pharaoh et al., 2011). The Gas Council GST2 Borehole (see Figure 3) proved 16m of grey-green and pink microcrystalline rock, thought to be of calc-alkaline chemistry, from 253 to 269 m; it is likely that, if part of a batholith, these rocks are considerably thicker.

4.2.3.3 Unnamed igneous intrusion, Cambrian–Ordovician — HSR

This unit is present from Congleton (Cheshire) to Newcastle-under-Lyme and near Loughborough, where it occurs just below the depth range of interest and is therefore not discussed further. Several other scattered occurrences of this unit are present in the subsurface in the East Midlands near Leicester and to the west of Oakham (Rutland) (Figure 17). These are all inferred to be part of the same intrusion, termed the 'Melton Mowbray granodiorite' (Carney et al., 2009). Although wholly concealed, it was proved by the Kirby Lane 1 Borehole (see Figure 3) from 395 m (base not proved), which showed the unit to be a coarse, inequigranular, xenolithic granodiorite (Carney et al., 2009). Aeromagnetic data indicate the intrusion to be flat topped; the upper part is likely weathered, which may have altered the clay mineralogy of the unit (Carney et al., 2009). The upper part is present within the depth range of interest, and its presence at deeper intervals has been extrapolated based on evidence from regional magnetic gradients.

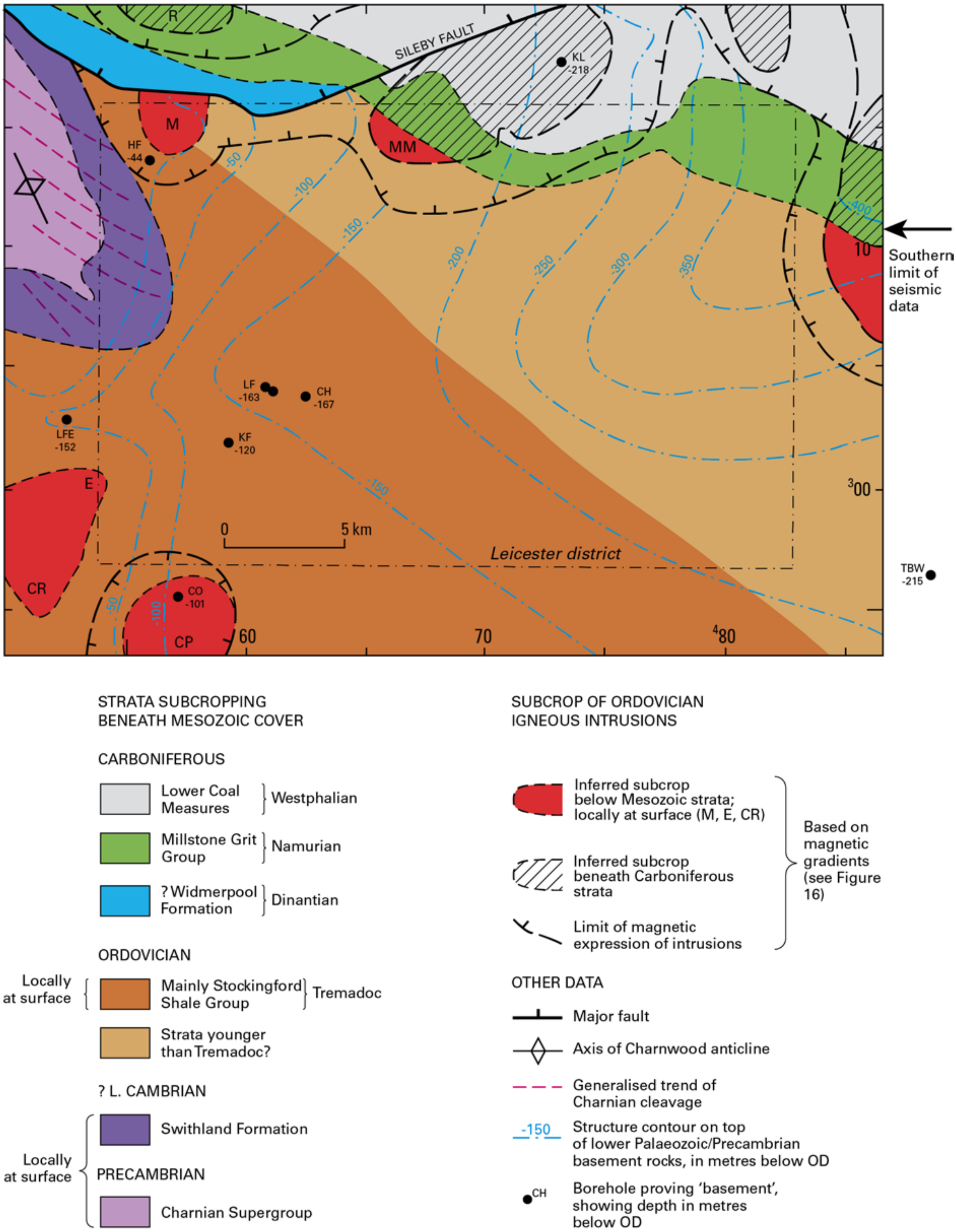


Figure 17 Distribution of the Melton Mowbray granodiorite (Carney et al., 2009). British Geological Survey © UKRI 2018.

4.2.3.4 UNDIVIDED NEOPROTEROZOIC ROCKS — HSR

These rocks are mapped within the NGS3D model to the south and east of Uppingham, where they are within the depth range of interest. They are not proved by boreholes within the area and so confidence on their distribution is considered low. They comprise basaltic andesite lavas in the Banbury district to the south of this area. There is potential that this unit could be equivalent to the Charnian Supergroup (discussed later), but because of the degree of uncertainty it has been coded as an alternative unit.

This unit is also mapped within the NGS3D model at depth between Telford, Shropshire, and Newcastle-under-Lyme, Staffordshire. These rocks are mapped within the depth range of interest in the Newport (Shropshire) district although they are not penetrated by boreholes in this area. The unit has also been identified below the depth range of interest to the north-west of Wolverhampton, where Bridge and Hough (2002) describe '180 m of mafic and felsic tuffs of Uriconian affinity' from the Heath Farm 1 Borehole (SJ90NW/49). As data proving this rock unit are sparse, and the unit has not been proved to the west of this region, the boundary of the Central England region is used as the limit of the unit.

4.2.3.5 Charnian Supergroup — HSR

The Charnian Supergroup comprises some of the oldest rocks preserved in southern Britain. It is present across a large part of the area, between Coalville (Leicestershire), to the west of Nuneaton, eastwards to Market Harborough (Leicestershire), with a southern extent in the Northampton district. The eastward extent of these rocks is presently unknown: borehole evidence from north-east of this area have been correlated with the Charnian Supergroup but this has been disputed (Pharaoh et al., 2011). Where present in the Central England region, the Charnian Supergroup is mapped within the depth range of interest, where it is thought to be contiguous with basement rocks at depth. Near Charnwood, the unit is also present at shallow depths of less than 200 m depth to the surface.

The unit is present in the eastern (Charnwood) terrane of the Midlands microcraton deep geological structure (Figure 18), where the Charnian Supergroup is over 3000 m thick (Pharaoh et al., 2011). The unit is described from numerous outcrops and a few borehole provings, and is also imaged with varying degrees of clarity on seismic reflection data. The Charnian Supergroup comprises well-bedded volcaniclastic rocks that were deposited in moderately deep water located close to a calc-alkaline volcanic arc (Pharaoh et al., 2011). Domes of dacite and andesite were intruded into these sediments (Pharaoh et al., 2011). Strata are well cleaved, with cleavage dated to 410 Ma, and a predominant strike to the west-north-west (Pharaoh et al., 2011).

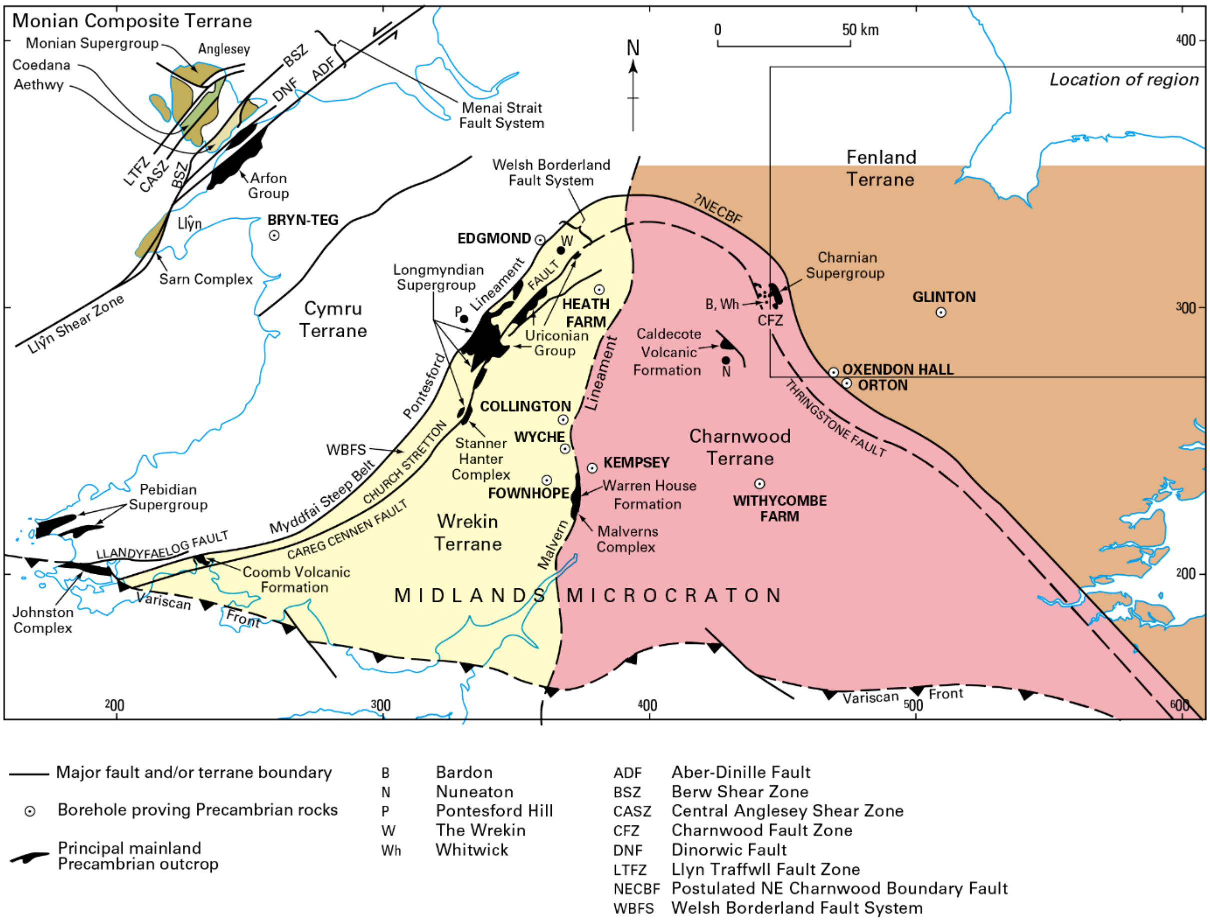


Figure 18 Locations of Precambrian outcrop, subsurface provings, structures and terranes in the region and adjacent areas (Pharaoh et al., 2011). British Geological Survey © UKRI 2018.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in the Central England region and shows their surface extent on a map (Figure 18). 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 structures 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 (RWM, 2016b). Their locations are indicated on the map in general terms and the nature of the folding is discussed.

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

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

5.2 REGIONAL TECTONIC SETTING

The surface and subsurface structure of the Central England region can be described in terms of four major structural events (orogenic cycles) that affected the region and surrounding areas: the Avalonian, Caledonian, Variscan and Alpine orogenies (Pharaoh and Haslam, 2018). Each orogenic cycle generally comprises a period of crustal extension with basin formation, followed by crustal shortening with basin deformation or (with less shortening) basin inversion. Distinct structural and sedimentary rock 'units' are associated with and separated by these events.

Most of the region is underlain by the Midlands microcraton (Wills, 1978; Pharaoh et al., 1987a; Lee et al., 1990; Smith et al., 2005), part of an Avalonian (Neoproterozoic) terrane incorporated into the metamorphic basement of Britain during the Caledonian Orogeny. The crust of the Avalonian terrane comprises volcanic, volcaniclastic and sedimentary rocks and intrusive plutonic complexes formed and accreted during late Precambrian (700 to 542 Ma) times (Pharaoh et al., 1987b; Pharaoh and Carney, 2000). The part of the Avalonian terrane incorporated within the Midlands microcraton is strongly heterogeneous, with possible sutures (e.g. the Malvern lineament) showing a complex history of Phanerozoic reactivation (e.g. East Malvern Fault). That part of the Avalonian terrane lying to the north of the microcraton experienced extension during early Palaeozoic times, associated with the development of the deep Welsh and Anglian Caledonide basins, underlying the north-west and north-east extremities of the region; the crust here remains thinner (about 30 km) than that of the microcraton (33 to 35 km) to this day (Chadwick et al., 1989; Ziegler, 1990). After several phases of subsidence in Cambrian to Silurian times, the Welsh and Anglian basins were inverted during the Acadian phase of the Caledonian Orogeny in Early Devonian (about 395 Ma) times, when construction of a new palaeocontinent, 'Laurussia', was completed. Acadian deformation was intense in the former basinal areas, producing strong folding and cleavage development (Soper et al., 1987); it was less intense within the microcraton, where cleavage is generally absent (Pharaoh et al., 1987b). Nevertheless, these low-grade metasedimentary, pre-Devonian strata are allocated to the 'basement' in this account.

Beneath the Permian to Mesozoic Cheshire basin, in the north-western part of the region, the early Palaeozoic Welsh basin is juxtaposed against the north-western margin of the microcraton. It comprises a several kilometres thick stack of basinal sequences ranging in age from Cambrian to Early Devonian (Woodcock, 1991), deformed into a slate belt in the Acadian phase of the Caledonian Orogeny, and hence referred to as the Welsh Caledonides. The boundary between microcraton and basin is marked by a complex zone of south-west to north-east trending faults known as the Welsh Borderland fault system (Woodcock and Gibbons, 1988), which were reactivated periodically throughout the early Palaeozoic. In the north-eastern part of the region, Caledonian basement rocks are deeply buried beneath sedimentary cover sequences. Boreholes demonstrate that the sub-Carboniferous basement is composed of low-grade metasedimentary rocks of Ordovician and Silurian age (Turner, 1949; Molyneux, 1991), and plutonic and volcanic igneous rocks (Pharaoh et al., 1991; 1993). The north-east boundary of the microcraton is poorly known at present (see later section on uncertainty). The Thringstone Fault, west of the Charnwood (Precambrian) inlier, forms at least part of this boundary.

In Early Devonian times, the continents of Armorica and other Gondwana-derived terranes collided with Laurussia during the Acadian and Bretonian deformation phases (Ziegler, 1990). The region lay within the southern margin of the Laurussian continent, forming part of the Variscan foreland. In Late Devonian (Frasnian–Fammenian) times, north–south crustal extension initiated the development of a set of linked half-graben (Leeder, 1982), part of a basin complex that extended from Ireland, eastwards through northern England, the East Midlands and Yorkshire into the Southern North Sea basin. The depocentres continued to grow as a result of pulsed rifting events into late Visean times resulting in strongly asymmetric rift basins, which were infilled largely with Tournaisian–Visean sediments of the older cover. The southern extremity of the Pennine basin, the Widmerpool half-graben, lies at the north-eastern edge of the region. The presence of a strong Caledonian and Avalonian basement structural grain gave rise to a predominantly south-west to north-east trend in the west, north-south in the centre and west-north-west to east-south-east in the east (Lee et al., 1990).

Original Tournaisian–Visean extensional faults were reactivated in compression during the late Carboniferous Variscan Orogeny. The style and magnitude of inversion depends on the orientation of these faults, and that of the basement faults that underlie them (Corfield et al., 1996). In the western part of the region, the most prominent inversion anticlines are associated with northerly trending structures such as the East Malvern and Apedale faults; in the eastern part of the region, north-west trending structures (e.g. the Thringstone Fault) are most significant. As these structures grew, their crests were eroded and clastic sediment was fed into small basins of latest Westphalian age.

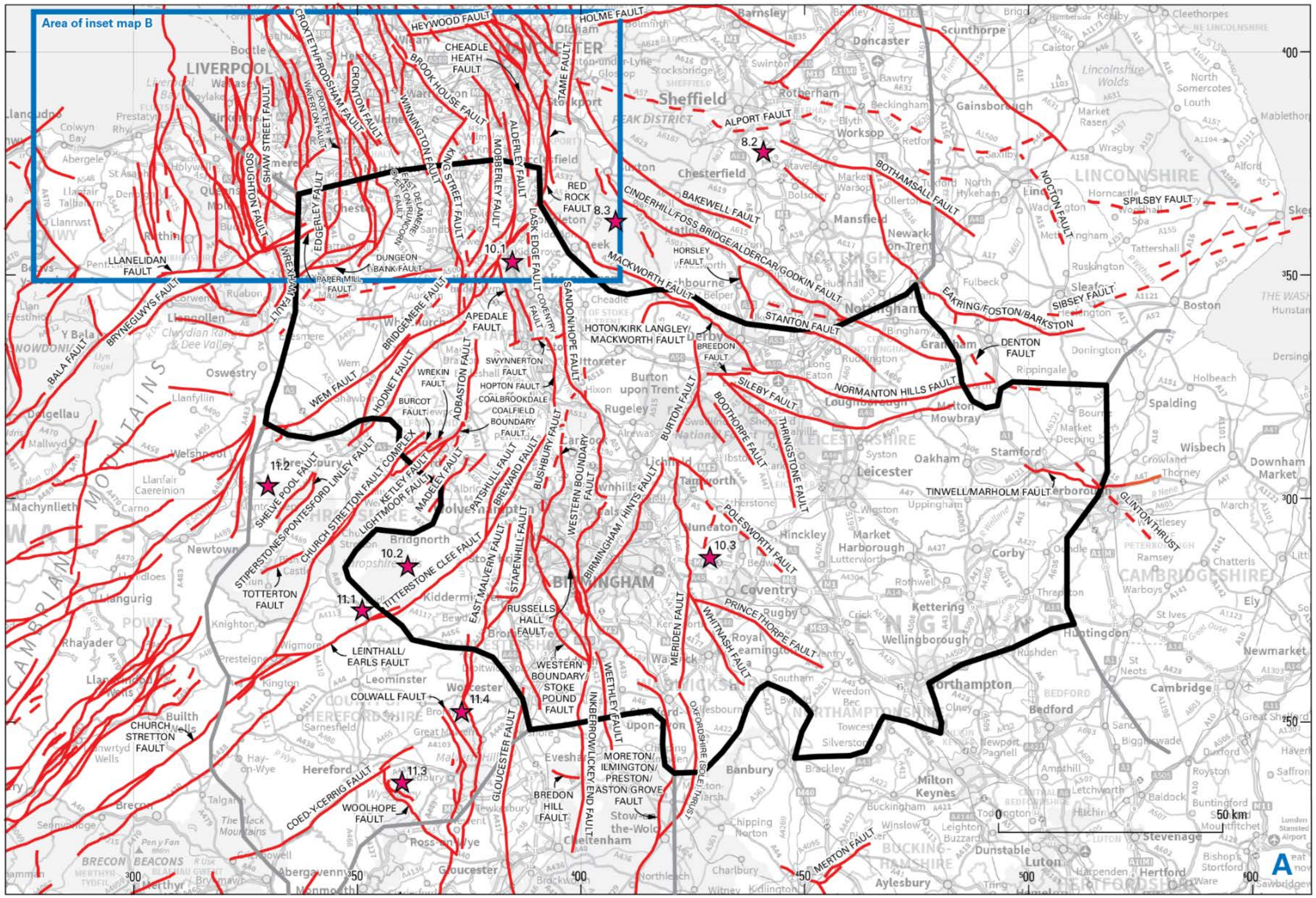
Following consolidation of the supercontinent of Pangaea in the Variscan Orogeny, in latest Carboniferous times, the crust of north-central Europe was intruded by alkaline and calc-alkaline magmas (Wilson et al., 2004), resulting from a combination of back-arc extension within the Tethys Ocean, transtension and regional thermal collapse (Stampfli and Borel, 2002; Scheck-Wenderoth et al., 2008). This led to extensional collapse of the orogen and localised rifting, e.g. in the Worcester graben, in the south of the region, and the Knowle, Needwood and Stafford basins, farther north. North-west-directed extension is inferred from Permian normal faulting in southern Britain (Chadwick and Evans, 1995). After thermal doming and significant erosion, the crust underwent regional subsidence following decay of the lithospheric thermal anomaly. The UK was now part of a major Triassic graben system extending throughout north-central Europe (Scheck-Wenderoth et al., 2008). Extensional reactivation of Variscan faults under an approximately east–west orientated extensional regime (Chadwick, 1997) commenced in late Permian times, resulting in the formation of a series of fault-controlled basins in a rift system extending from the English Channel (south of the region) to the East Irish Sea basin. Those basins lying within the region are, in order of decreasing size: the Cheshire; Stafford; Needwood; Hinkley; and Knowle basins, and the Bratch graben. Locally up to 3500 m of strata were deposited within these basins by the end of the Triassic. There are also thin Permo-Triassic strata on the eastern England shelf, at the eastern extremity of the region, where crustal extension was less, graben failed to develop and subsidence rates were much slower than in the west of the region. Crustal extension and the development of syndepositional normal faulting was rapid during the Early Triassic, but less active in the Mid to Late Triassic.

The post-Triassic evolution of the region is poorly constrained due to the paucity of preserved strata. The region occupied a relatively stable, slowly subsiding platform between more rapidly subsiding basins, and the Jurassic succession was much affected by eustatic influences. Post-Jurassic movements can be demonstrated on a number of faults, including the Normanton Hills–Hoton, Sileby, Princethorpe and Tinwell–Marholm faults (Pharaoh et al., 2011; Hains and Horton, 1969). During the Cenozoic, the region lay in the foreland of the Alpine-Carpathian Orogen and was affected by a number of pulses of inversion throughout this time. There has been considerable debate about which of these events was most significant in shaping the Cenozoic exhumation of the region. Brodie and White (1994) and Rowley and White (1998) have argued that regional uplift associated with Paleocene magmatism has been the most significant factor. Other authors have argued that the final, Savian (end-Oligocene/Early Miocene) pulse of the Alpine Orogeny caused significant uplift in the Sole Pit (Glennie and Boegner, 1981) and the East Irish Sea (Holliday, 1993; Cope, 1997; Green et al., 2000; Holford et al., 2009), Weald and Cleveland basins (Whittaker, 1985), beyond the limits of the region.

5.3 MAJOR FAULTS

The major faults selected from analysis of the UK3D model and published maps in the region (Figure 19) exhibit a variety of orientations and evolutionary histories, as a consequence of the complex structural history described. In this description, 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. The domains are roughly equivalent to the individual western, central and eastern areas described in the Regional Summary for Central England. The terms ‘older cover’ and ‘younger cover’ used in this description refer to strata of Devonian to Carboniferous, and Permian to Jurassic, age respectively.

As this region is dominantly occupied by cover sequences at crop, folding is usually related to inversion of the cover sequence and localised to the major fault zones that have suffered such inversion.



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★ Areas of folding

Major faults transecting depth range of interest

Major fault terminating in depth range of interest

Central England and adjoining areas

Figure 19 A) Major faults and folding in the Central England region. B) Inset map, area of inset shown in blue on map A. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

5.3.1 Western area

In the western part of the region, faults have a predominantly south-west trending orientation. Hydrocarbon exploration reflection seismic coverage is good in the Cheshire basin, but absent outside it, e.g. in Shropshire, where faults are identified and located exclusively by surface mapping. The consistent south-west trend is a consequence of a complex reactivation history originating in the Caledonide basement. The most important lineaments in the Caledonide basement are those of the Welsh Borderland fault system (Woodcock and Gibbons, 1988), which formed the boundary between the Midlands microcraton and the Welsh basin throughout early Palaeozoic times.

Precambrian basement (Uriconian Volcanic Group and Longmyndian Supergroup) is incorporated in inferred transpressional duplex structures within this zone, between the Pontesford lineament–Hodnet Fault in the west, and the parallel Church Stretton fault complex lying about 12 km to the east. The north-east trending Church Stretton fault complex has a mapped length of at least 121 km, mostly to the south-west in the adjacent Welsh Borderland region, and both normal and reverse throws of up to 935 m in early Palaeozoic strata at crop. The Titterstone Clee Fault is at least 85 km long and has a reverse throw of about 250 m in early Palaeozoic strata. It splays off the Church Stretton Fault to the south-west of Ludlow and turns north-east parallel to it, controlling the eastern margin of the Permo-Triassic Stafford basin, as the Pattingham Fault. The north-north-east trending Patshull and Breward faults are antithetical to this system, both with normal throws of 265 to 300 m in Permo-Triassic strata. The Lightmoor Fault lies parallel to the Church Stretton fault complex, and about 8 km farther east, with a normal throw of 270 m in early Palaeozoic strata.

The north-east-trending Pontesford lineament has a mapped length of 117 km including its extension to the north-east into the region along the Hodnet–Red Rock fault system (Smith et al., 2005). The Hodnet Fault has a throw exceeding 200 m in Permo-Triassic strata (Chadwick et al., 1999). The Red Rock Fault locally has a normal throw of 463 m affecting Permo-Triassic strata and moderate westerly dips (45° to 60°).

The basement of the Cheshire basin largely comprises metasedimentary rocks. The Wem, Bridgemere and Red Rock faults are the most important syndepositional, basin-controlling normal faults at the eastern edge of the basin (Hains and Horton, 1969), with a combined westward downthrow exceeding 4000 m at the base Permo-Triassic level (Chadwick and Evans, 1995). They comprise a series of large, north-west-dipping normal faults, downthrown to the west, lying along a major lineament in the early Palaeozoic basement reactivated from the Mid Ordovician and possibly Proterozoic times onwards (Smith et al., 2005). The Wem Fault has a throw exceeding 2500 m at the base Permo-Triassic level (Evans et al., 1993; Chadwick, 1997). The Bridgemere Fault has a much smaller westerly throw of about 320 m, and this is in the Carboniferous at depths greater than 4000 m. The combined downthrow in the Permo-Triassic strata gradually decreases northwards along the system to a few hundred metres or less in the north (Evans et al., 1993; Chadwick, 1997).

The north-trending Alderley Fault is a splay within the hanging wall of the Red Rock Fault, cutting across the Sandbach–Knutsford basin for some 30 km. It has a throw of about 800 m in Carboniferous strata, but again this is below the depth of interest. Earlier syndepositional movements on the fault can be interpreted by the change in thickness of the Tournaisian–Visean sequence in the hanging-wall block. The Mobberley Fault is parallel to the Alderley Fault and has a similar downthrow in Carboniferous strata.

The Brook House–King Street fault is a complex, sinuous structure downthrown to the east comprising a number of segments with up to 430 m of Variscan reverse displacement, and 400 m of normal downthrow in the Triassic (Chadwick et al., 1999).

The Bala–Bryneglwys–Llanelidan fault zone of the Wales region extends north-eastward in the subsurface beneath the Permo-Triassic cover of the Cheshire basin, where it appears to truncate against the major Edgerley fault zone (Smith et al., 2005), with up to 1850 m downthrown to the west. Evidence of mild Variscan fault reversal is seen in the development of a local fault-controlled inversion anticline above the base of the Coal Measures Supergroup. Further substantial normal movement occurred again in Permo-Triassic times, and it is possible that there was some reverse movement, perhaps in Cenozoic times, although this cannot be proved.

The Croxteth–Frodsham fault system is another curviplanar structure with an eastward downthrow exceeding 200 m in the Permo-Triassic, and considerably more (greater than 840 m) in the Carboniferous. The development of this, and the adjacent East Delamere–Overton Fault, is likely to have been strongly influenced by detachment in deep salt horizons.

5.3.2 Central area

In the central part of the region, faults have a predominantly north–south orientation. Reflection seismic coverage varies from good over the main Permo-Triassic graben to poor over the coalfield areas. The north-trending Malvern lineament has a mapped length exceeding 117 km, mostly to the south, in the adjacent Welsh Borderland region. The lineament is inferred to have originated in late Neoproterozoic times, as a suture zone between two crustal terranes of contrasting crustal composition and history: the Wrekin and Charnwood terranes (Pharaoh et al., 1987b; Pharaoh and Carney, 2000).

In the Malvern Hills, the Precambrian basement is overthrust westward across coevally folded Silurian and Devonian strata. Furthermore in the Abberley Hills, intense folding of latest Westphalian strata (Dunning, 1992) demonstrates the Variscan age of this inversion. The East Malvern Fault is an extensional reactivation of the Malvern lineament in Permian to Jurassic times (Chadwick and Evans, 1995). The fault developed as an extensional 'shortcut' with up to 2500 m of normal displacement. It is likely (although not proven) that normal displacements, downthrown to the east, continued into Jurassic and Early Cretaceous times.

Within the Worcester graben, at the southern margin of the region, several north-trending faults reflect the structural grain established by the events described previously. These include the Gloucester Fault (67 km mapped length) with 590 m westward normal throw of Triassic strata; the Inkberrow Fault, with up to 1050 m of Early Triassic syndepositional normal displacement (Chadwick and Evans, 1995), and the Lickey End Fault, with about 200 m normal downthrow in Triassic to Jurassic strata. The Clotton Fault is a north–south-trending normal fault known to downthrow Permo-Triassic strata to the east by about 300 m (Earp and Taylor, 1986).

The presumed extension of the Malvern lineament beyond the northern apex of the microcraton is problematic. Dunning (1992) has proposed that north–south elements such as the Sandon and Lask Edge faults, with downthrow to the east, may play a role, but the BGS surface mapping suggests that they are not directly linked to the Malvern lineament. The Stapenhill, Bushbury, Apedale and Enville faults may represent alternative extensional reactivations of the lineament.

The north-north-west-trending Lask Edge Fault is an important Carboniferous structure located near the northern apex of the Midlands microcraton, to the west and south-west of the exposed Derbyshire carbonate platform, originally inferred from gravity data (Lee, 1988). It has a normal downthrow of about 640 m in early Carboniferous strata. It is possible that it is linked to the north-west trending Kingsley Fault just to the south-east, across which the seismic data indicate a considerable thickening of the Tournaisian–Visean succession. However, it may also continue *en échelon* into the Sandon Fault, with about 260 m of normal downthrow, which defines the western margin of the Permo-Triassic Needwood basin.

The west–east-trending Swynnerton Fault, with about 300 m of southward throw, is anomalous in trend. It may form a 'transfer zone' at the northern edge of the Stafford basin. In the hanging wall of the Apedale Fault, the Carboniferous succession is deformed into a series of north-trending folds (the 'eastern folds' of Rees and Wilson, 1998), which were formed during Variscan compression (see section 5.4, Folding). The Bushbury Fault, with about 220 m westward normal downthrow, is the controlling fault for the Stafford basin, at the western boundary of the south Staffordshire coalfield.

The Bratch graben forms a narrow north–south-trending graben linking the Stafford and Worcester basins. It is bounded on the west by the Enville Fault and on the east by the Stapenhill Fault, with about 250 m of westward normal downthrow in Permo-Triassic strata, linking the Bushbury and East Malvern faults.

The Needwood basin is faulted on both margins, the Sandon Fault lying on the western margin and the south-west to north-east-trending Burton Fault on the east, with about 670 m of throw at the Carboniferous level.

The Sandon Fault is 40 km long and currently downthrows to the east; during Variscan inversion, both this and the Burton Fault underwent reversal in their northern parts. The Carboniferous succession that lies between the Sandon and Burton faults has been subjected to inversion; most of the Westphalian succession was eroded prior to the deposition of the Permo-Triassic strata (Smith, 1985; Smith et al., 2005).

The north-north-east trending Permo-Triassic Knowle basin is bounded to the west by the Birmingham–Hints fault, with about 350 m of downthrow to the south-east, and to the east by the Western Boundary Fault (of the Warwickshire coalfield), and the Meriden Fault, with about 600 m of throw at the base Triassic level. The north-north-east-trending Birmingham Fault is 20 km long and passes *en échelon* into the Hints Fault. The Russell's Hall reverse fault almost links the Western Boundary and Eastern Boundary–Hope faults on the eastern boundary of the south Staffordshire coalfield (Waters et al., 1994). It has a net reverse displacement along much of its length, locally exceeding 200 m. In the late Carboniferous, these faults acted as reverse faults, uplifting the basement of the Knowle graben to form a horst (Wills, 1956) to the east, and overthrusting Westphalian strata to the west. Movement on the Western Boundary Fault is thought to have started during deposition of late Carboniferous strata during early Variscan inversion. Movement is thought to have occurred in several phases.

Towards the eastern part of the central region, faults have a predominantly north-west trend. Seismic coverage is generally very poor in this area. Faults trending north-west (e.g. the Thringstone, Boothorpe and Polesworth faults) exhibit a strong Variscan reverse movement, separating domains 5 to 10 km wide, affected by asymmetric folds overturning to the south-west (e.g. the Breedon and Ashby anticlines and the Melbourne Syncline). These folds exhibit steep limbs in the footwall blocks of the reverse faults. This pattern of deformation, concentrated in discrete zones, is suggestive of the reactivation of zones of pre-existing anisotropy within the pre-Carboniferous basement.

The north-west trending Thringstone Fault has a complex history. Reverse movement of up to 550 m (Worssam and Old, 1988) is estimated during late Carboniferous and early Permian times, with a comparable amount of Triassic downthrow.

The Boothorpe, Warton and Polesworth faults were reactivated as normal faults during Permo-Triassic extension; all trend approximately north-west, dipping to the north-east. The Boothorpe Fault lies subparallel to the Thringstone Fault; the estimated Variscan downthrow to the west was about 320 m, which was followed by Triassic downthrow to the east (Carney et al., 1999).

The north-west trending Hinkley basin is fault bounded on its western margin. This can be demonstrated in the north along the Warton Fault; elsewhere, however, seismic data are lacking and the relationships at the basin margins remain ambiguous. The Warton Fault juxtaposes early Palaeozoic rocks of the Hinkley basement with the concealed northerly extension of the Nuneaton Anticline, above Carboniferous strata to the south-west. It passes *en échelon* into the Polesworth Fault, which downthrows the base of the early Palaeozoic strata about 260 m to the north-east.

The north-north-west-trending Whitnash Fault has about 315 m downthrow at the early Palaeozoic level, but rather less in the Triassic.

The west-north-west-trending Princethorpe Fault has a northward downthrow of 150 m.

5.3.3 Eastern area

In the eastern part of the region, faults have a predominantly west-north-west orientation. Seismic coverage is good as a consequence of a dense network of high quality hydrocarbon exploration data. The nature of the inferred north-east boundary of the Midlands microcraton (and Anglo–Brabant massif) is poorly known, but the basement of this region, typically at depths of 200 to 400 m, is thought to belong to the Eastern England or Anglian Caledonides (Pharaoh et al., 1987a), and a west-north-west-trending structural grain is inferred (Lee et al., 1990; Pharaoh et al., 2011). The Thringstone Fault lies on the south-west flank of the Charnwood high, separating it from the Leicestershire coalfield. It trends north-north-west to north-west, dips at 40^{o} to the north-east and can be mapped over a distance of about 32 km. Reverse movement of up to 550 m (Worssam and Old, 1988) is estimated during late Carboniferous times, emplacing a succession ranging in age from the Precambrian to Namurian over Coal Measures to the south-west (Butterley and Mitchell, 1946) and the fault is interpreted as a major Variscan inversion structure (Smith et al., 2005). It likely also had an earlier, Caledonian, history (Pharaoh et al., 2011). The CHARM seismic line (Maguire, 1987) imaged the fault as a north-east-dipping zone.

The presence of cleaved rocks on the Hathern shelf and the grade of metamorphism suggest that both the shelf and Charnwood massif lie within the Caledonide domain. Unfortunately the nature of the remaining 150 km of the unexposed north-east boundary of the Midlands microcraton is unknown. It could be faulted, as at Thringstone, and analogous to the Welsh Borderland fault system on the north-west boundary (Pharaoh et al., 1995; 2011) or, less likely, there could be some form of transition such as a sedimentary onlap of Phanerozoic cover onto the basement (Woodcock, 1991). Both its geometry and history are highly conjectural.

The Mackworth–Normanton Hills–Hoton fault system, with a mapped length of 117 km, formed a major Tournaisian–Visean syndepositional extensional fault system, downthrow to the north, that controlled the development of the southern boundary to the Widmerpool half-graben and marks the northern margin of the

Hathern shelf area (Ebdon et al., 1990; Carney et al., 2001) and thus the Anglo–Brabant massif. The fault system lies sub-parallel to (and about 10 km north of) the inferred north-east boundary of the Midlands microcraton. It also lies close to the inferred boundary of the Charnwood and Fenland Precambrian basement terranes (Pharaoh and Carney, 2000).

The north-west trending Mackworth Fault lies in the hanging wall of the Thringstone Fault and is a major Carboniferous and Permo-Triassic normal fault, downthrown to the east, mapped from Mackworth, south of the Peak District, to Derby. Late Palaeozoic strata show about 400 m of downthrow.

The Normanton Hills Fault links to the Mackworth Fault near Derby. Maximum throw at the base Carboniferous level is 4000 m, rather less at the top Visean level (Pharaoh et al., 2011). At depth, the fault apparently passes into a more gently dipping detachment surface (Fraser and Gawthorpe, 2003) eventually becoming a planar detachment with a relatively low dip of about 40° to the north-north-east, at depths greater than 5 km. The amount of Visean downthrow on the fault system was reduced by subsequent (Variscan) reversal.

The Hoton Fault, the easternmost component of this fault system, was first recognised in the Mesozoic cover and named by Fox-Strangways (1905). It is a normal fault, trending west-north-west and downthrows the Lias Group by 95 m to the north (Brandon, 1996; Carney et al., 2001), but the Palaeozoic throw is significantly greater. Eastwards beyond Asfordby it develops a number of strands with reduced throws, and eventually dies out south of the Foston high, just outside the eastern extremity of the region. An antithetic fault to the Normanton Hills–Hoton fault at Rempstone was reactivated in post-Triassic times, possibly by Alpine compression (Pharaoh et al., 2011).

The east-south-east-trending Sileby Fault lies subparallel to the Hoton Fault. It defines the southern limit of the Hathern shelf and is offset by north-north-west-trending faults associated with the uplift of the Charnian basement in the Charnwood Anticline (Carney et al., 2001). Up to 1650 m of normal downthrow to the base Carboniferous level to the north-east is suggested by the preserved stratigraphical thicknesses observed on seismic sections. During Late Devonian to Chadian times, the Sileby Fault was the major basin-bounding fault of the Widmerpool half-graben system (Fraser and Gawthorpe, 2003), as shown by the relatively thick, anhydrite-bearing Tournaisian strata present on the shelf, and proved by the Hathern 1 Borehole (Falcon and Kent, 1960). Triassic and Early Jurassic strata exhibit about 200 m of northward normal downthrow.

The Cinderhill–Foss Bridge Fault delimits the southern edge of the Carboniferous Nottingham platform (Pharaoh et al., 2011) and forms the north-east hinge of the Widmerpool half-graben. The Cinderhill Fault, mapped from surface exposure and mine records, was reactivated during Permo-Triassic extension, with up to 200 m of downthrow to south. The Tinwell–Marholm Fault is a west–east-trending fault with a northward downthrow affecting Mid Jurassic strata, which was implicated in the 1813 and 1844 Stamford earthquakes by Davison (1924). Hains and Horton (1969) inferred a post-Jurassic age for this.

5.4 FOLDING

Most of the region is covered by Permian, Triassic and Jurassic strata, which are not significantly affected by folding. In the eastern part of the region, on the eastern England platform, regional dips rarely exceed 2°. In parts of the coalfield areas (Coalbrookdale, south Staffordshire, north Staffordshire, Warwickshire, north-east Leicestershire (Figure 19)) the older cover sequence rocks of Carboniferous age and older are strongly affected by folding associated with Variscan inversion. The axial trends of such inversion anticlines match the fault with which they are paired, and dips rarely exceed 25°. The tightest Variscan folds are in the Potteries Syncline of north Staffordshire (Figure 19), where a convergence of basement structural trends at the northern edge of the Midlands microcraton has focused and intensified deformation. Even here, the Carboniferous stratal dips do not exceed 30°.

Early Palaeozoic strata at surface down to the 1000 m depth cut-off are largely restricted to the western part of the region. They exhibit a gentle south-eastward regional tilt in the area south-east of the Welsh Borderland fault system (Figure 19). Crossing the latter into the Welsh basin (and in the substrate of the Cheshire basin at depths exceeding 2000 m), these strata become increasingly cleaved and affected by tight, penetrative folding, resulting in steep dips and fracture-enhanced, potential fluid-migration pathways.

5.5 UNCERTAINTY

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, each containing multiple fractures. The portrayal of such faults as a single line on the geological map is therefore a generalisation.

Areas where there is limited or no subsurface data, e.g. in Shropshire and Northamptonshire in the present case, carry the greatest degree of uncertainty in terms of the presence, location and nature of subsurface structures such as faults. A particular case in point is the nature of the inferred eastern boundary of the Midlands microcraton. The approximate location has been defined using biostratigraphical evidence from early Palaeozoic strata (Molyneux, 1991) and stratigraphical and structural evidence (Pharaoh et al., 1987a; Woodcock and Pharaoh, 1993), but its nature is a matter of conjecture (Woodcock, 1991). Discontinuities in the gravity and magnetic potential field data (Lee et al., 1990) suggest that it may be faulted, as in the Welsh Borderland lineaments, but if so, significant post-Caledonian reactivation is apparently absent. Perhaps the orientation with respect to subsequent orogenic stress fields was incompatible with reactivation; maybe the boundary was healed by magmatic intrusion? The issue is important because it is not possible to predict the nature and composition of the basement over a large area of eastern England as a consequence of our ignorance.

The presence, and 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. Within the Central England region, the distribution of seismic lines is extremely patchy, with coverage provided over the north-western, central and north-eastern parts. In these areas, particularly where the lines form a close grid, the recognition and location of subsurface faulting and folding carries higher confidence and is best constrained. Seismic coverage is absent in Shropshire and the eastern part of the area, and poor in the central area, where only spatially restricted Coal Authority data are available. Principal uncertainties in seismic location depend on the spacing and quality of the seismic grid; migration (or not) of the data; depth conversion of the interpretation. Experience shows that under good conditions, uncertainty of X,Y 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 Central England region, the regional groundwater flow systems, and any units or structures that may lead to the effective separation of deep and shallow groundwater systems, including evidence based on groundwater chemistry, salinity and age. It describes the hydrogeology of PRTIs (or their parent units), principal aquifers and other features, such as rock structure or anthropogenic features (including boreholes and mines) that may influence groundwater movement, and interactions between deep and shallow groundwater systems. It also includes a note on the presence or absence of thermal springs (where groundwater is >15º C) that may indicate links between deep and shallow groundwater systems.

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

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

6.2 GROUNDWATER SYSTEMS IN THE CENTRAL ENGLAND REGION

There is some information related to groundwater in the depth range of interest, i.e. between 200 and 1000 m depth, in the Central England 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 less than 200 m, although Environment Agency (2016) reports that groundwater may be being extracted from as deep as 600 m from the Inferior Oolite Group in the east of the region. 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. 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.

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The regional groundwater flow systems in the Central England 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 hydraulic boundary conditions, such as rivers in hydraulic connection with active groundwater systems.

The GVS for the Central England region (Table 3) divides rock units into three age ranges: younger sedimentary rocks, older sedimentary rocks and basement rocks. Some of the rock units are considered to represent PRTIs present within the depth range of interest, between 200 and 1000 m below NGS datum. These include a number of lower strength sedimentary rocks units (LSSR), as well as evaporite (EVAP) and higher strength rock (HSR) units. In the north-western and central parts of the region, the bedrock geology is structurally relatively complex and dominated by a sequence of fault-bounded basins and structural highs separated into distinct fault blocks. In the east, younger rocks are tilted gently towards the south-east and are more continuous.

In the north-west of the region, the most important principal aquifer in the region, the Sherwood Sandstone Group, is present from the land surface down into the depth range of interest within the Cheshire basin. In the centre of the basin, Jurassic rocks and the Mercia Mudstone Group confine the Sherwood Sandstone Group, while at the margins of the basin the sandstones form prominent ridges where the aquifer is recharged. Most groundwater movement in the Cheshire basin occurs at shallow depths (down to approximately 100 m) (Lucey, 1987) and the average residence time of the shallow groundwater system has been estimated to be approximately 275 years (Griffiths et al., 2002). At greater depths (below about 400 m) groundwater flow is more limited. Stable isotopes indicate that this groundwater is older, probably having been recharged in the Late Pleistocene (Griffiths et al., 2002). Groundwater flow in the more permeable formations at a subregional scale may be expected to be towards the centre of the basin. However, compartmentalisation of the groundwater system is common in the Permo-Triassic sedimentary rocks and stratigraphically deeper aquifers (such as the Warwickshire Group) due to both relatively low permeability faults and beds. Consequently, identification of coherent variations in groundwater flow and heads at the subregional scale is highly problematic. The eastern margin of the Cheshire basin is defined by the Wem–Red Rock fault system, to the east of which older rocks crop out in the central area of the region.

East of the Wem–Red Rock fault system, in the centre of the region, there is also a lack of subregionally coherent trends in groundwater heads and flow. This area is structurally complex, comprising faulted basins and up-faulted blocks that act to compartmentalise groundwater systems, with many smaller Permo-Triassic basins and uplifted blocks of Carboniferous rocks. In this area groundwater levels are influenced by surface topography (Pearson, 2008). Hydraulic gradients are generally relatively flat within the basins but steepen rapidly towards the basin margins, under Carboniferous rocks, where recharge is greatest, and against major faults (Bridge and Hough, 2002). Also in this area, lithological variation within sub-basins may affect groundwater flow. For example, the Chester Formation may act as an aquitard between the Triassic sandstone units above and Permian sandstone units below it (Allen et al., 1997; Barclay et al., 1997; Old et al., 1991). Where the Mercia Mudstone Group overlies the Sherwood Sandstone Group aquifer in the basins it may cause artesian conditions (Burley et al., 1984; Whitehead et al., 1927).

Within the central area, groundwater flow in the Worcester basin is controlled by heads in the high ground to the west, north and east. Direct recharge of the Permo-Triassic sandstones occurs in the west and north of the basin, and indirect recharge occurs by downward vertical flow below the high ground of the Cotswolds (see the Bristol and Gloucester region companion report). Most water entering the Permo-Triassic sandstone in the outcrop area is discharged to local river systems, but some flows into the confined aquifer. The pattern of basinward flow results in predominantly horizontal flow in the Permo-Triassic sandstones, and upward (Barclay et al., 1997) vertical flow in the Mercia Mudstone Group and Lias Group, in the central parts of the basin, to outlets in the Severn flood plain (Downing and Gray, 1986). Artesian conditions have also been encountered north of Stratford-upon-Avon, in the Helsby Sandstone Formation at Armscote, north of Shipston-on-Stour (Edmonds et al., 1965), and at Cookley Pumping Station, Kinver, Stourport and Kidderminster (Allen et al., 1997).

In the east of the region, across an area extending southwards from Grantham to Evesham, there is a succession of Permian and younger bedrock that is tilted gently towards the south-east and which overlie the East Midlands shelf, comprising rocks of Carboniferous age or older. Groundwater flows broadly down dip in the more permeable units in this younger cover sequence. For example, groundwater head contours are widely spaced in the Sherwood Sandstone Group across the area, with a very shallow gradient in an easterly direction (Institute of Geological Sciences, 1981), although around larger abstractions the hydraulic gradient may be locally reversed, causing recharge from surface water courses. In the underlying older Carboniferous units, groundwater is saline and believed to have originated from the diagenesis of Carboniferous marine and brackish waters and possibly some Permian marine waters. There is a flow of water from west to east through the Carboniferous aquifers in the east. The water is possibly moving into the Permian and Triassic strata where these overlie Carboniferous aquifers in the general area of Grantham and possibly further to the east.

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 sedimentary strata of Permian to Jurassic sediments and younger
- a groundwater system in the older, Devonian and Carboniferous, sedimentary strata sequence
- a groundwater system in the relatively low permeability basement rocks and igneous intrusions of Proterozoic to Silurian age

Rocks from all three of these systems are found in the depth range of interest across the region. There are a range of pathways (both known and potential) for groundwater movement between these groundwater systems, associated with both regional-scale structures and anthropogenic features. 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 Permian to Jurassic sedimentary strata

6.3.1.1 Great Oolite Group and Inferior Oolite Group

Both the Great Oolite Group and the Inferior Oolite Group have very limited presence in the region. They do not provide significant groundwater resources and neither is found in the depth range of interest. Consequently, they are not considered further.

6.3.1.2 Lias Group

The Lias Group comprises units of mixed lithology comprising siltstones, mudstones, ferruginous sandstones, bioclastic limestones and cementstones (Carney et al., 2004; Hobbs et al., 2012). The Lias is present in the east of the region, and dips gently to the south-east where it is overlain by younger Jurassic rocks (Inferior, Great Oolite and Ancholme groups).

The greatest cause of variation in hydrogeological characteristics in the Lias Group is due to differences in lithology and weathering (Hobbs et al., 2012). The upper Lias mudstones yield little or no groundwater (Edmonds et al., 1965; Williams and Whittaker, 1974). The Marlstone Rock Formation is a local, fracture-flow dominated aquifer (Jones et al., 2000).The Blue Lias Formation has a relatively low permeability, but locally supplies groundwater from fractured limestones (Edmonds et al., 1965; Barclay et al., 1997). There is no information about the hydraulic properties of the unit below 200 m depth in the references reviewed for the Central England region.

6.3.1.3 Mercia Mudstone Group

The Mercia Mudstone Group comprises mudstone and siltstone. Rare beds of mostly very fine-grained sandstone compose about 10 per cent of the succession, and thick beds of halite are predominantly present in basins bound by faults.

In general, the Mercia Mudstone Group is predominantly poorly permeable. It forms a confining upper limit to the underlying Sherwood Sandstone Group aquifer (Jones et al., 2000). For example, in the East Midlands many boreholes in the Mercia Mudstone Group are dry (Jones et al., 2000) and at Melton Mowbray a 300 m deep borehole only yielded small quantities of groundwater; the borehole was open between the Scunthorpe Mudstone Formation (Lias Group) and the Mercia Mudstone Group (Carney et al., 2004). However, thin, well-cemented sandstone and siltstone horizons known as ‘skerries’ may contain and transmit limited quantities of groundwater through fractures (Jones et al., 2000). Groundwater in the lower formations can be in hydraulic continuity with the underlying Sherwood Sandstone aquifer (Jones et al., 2000).

Groundwater in the Mercia Mudstone Group is generally hard, highly mineralised and non-potable due to dissolution of evaporite minerals such as gypsum and anhydrite, which occur in beds or cements (British Geological Survey, 1989). There is no systematic information about the hydrogeological properties of the low permeability intervals of the Mercia Mudstone Group (mudstones and evaporites) at depths in excess of 200 m in the references reviewed for the Central England region.

6.3.1.4 SHERWOOD SANDSTONE GROUP AND LENTON SANDSTONE FORMATION

The Sherwood Sandstone Group (incorporating the underlying Lenton Sandstone Formation in UK3D) comprises sandstones with subordinate mudstones and siltstones. It crops out around the south Staffordshire coalfield and the margins of the Stafford basin. Elsewhere it is generally confined by the overlying Mercia Mudstone Group. It overlies either sandstones of Permian age, with which it is in hydraulic continuity (Allen et al., 1997) or the Warwickshire Group. In Shropshire, the Sherwood Sandstone Group crops out on the southern rim of the Cheshire basin and is bounded to the west and south by older Palaeozoic or Precambrian rocks. Within the group, younger formations tend to progressively overlap older ones in extent in these basins. These Permo-Triassic sandstones of the West Midlands typically act as a single hydrogeological unit (Allen et al., 1997).

In the Central England region the Sherwood Sandstone Group comprises the Helsby Sandstone, the Wilmslow Sandstone and the Chester formations, all of which are in hydraulic continuity (Allen et al., 1997). In the northern East Midlands the Sherwood Sandstone Group comprises the Chester Formation (formerly the Nottingham Castle Sandstone Formation) and is underlain by the Lenton Sandstone Formation (formerly a component of the Sherwood Sandstone Group), a separate unit underlying the Sherwood Sandstone Group that is in part a lateral equivalent of the Permian Edlington and Roxby formations.

In general, the Helsby Sandstone Formation is a poor aquifer relative to the Wilmslow Sandstone and Chester formations (Allen et al., 1997); pebbly horizons within it, and within the Chester Formation, are generally more cemented, have lower porosities and are slightly less permeable than the rest of the Sherwood Sandstone Group (Allen et al., 1997), although variations in cementation with depth may not be ubiquitous throughout the strata at depth (Downing and Gray, 1986). Mudstones are also most common in the Chester and Helsby Sandstone formations and might form local hydraulic barriers and isolation of layers of sandstone, which can give rise to perched water tables (Allen et al., 1997).

Lithological variation, rather than depth below ground level, acts as the major control on intergranular hydraulic conductivity in the top 150 m (Allen et al., 1997). The degree of fracture flow varies between lithologies (Allen et al., 1998). For example, in the Cheshire basin the Chester Formation is the most significant aquifer unit (Allen, et al., 1997). Fractures are most extensive and open in this formation (Allen et al., 1998) due to its competence (Allen et al., 1997). The Wilmslow Sandstone Formation can be highly fractured within 150 m of the ground surface (Allen, et al., 1997) but fractures are smaller, less extensive and have lower flows (Allen et al., 1998) because it is poorly cemented (Allen et al., 1997). In the West Midlands, at Webheath (Redditch), the permeability of the Helsby Sandstone Formation appears to increase with depth reflecting the number, distribution and efficiency of fractures encountered by a particular borehole (Allen et al., 1997).

The groundwater chemistry of the Permo-Triassic sandstones in the Cheshire basin is highly variable (Griffiths et al., 2002; Griffiths et al., 2003). Faulting and clay-rich horizons have compartmentalised the aquifer causing considerable spatial heterogeneity of most chemical parameters and solute concentrations (Griffiths et al., 2003). Water in the East Cheshire–Manchester area may be impacted by the underlying Pennine Coal Measures Group and overlying superficial deposits (Griffiths et al., 2003). Groundwater from the edge of the Cheshire basin has a range of stable isotopic values for δ^2H and $\delta^{18}O$; from meteoric to close to sea-water in composition. More $\delta^{18}O$-depleted waters have a higher Cl content; implying that the longer-residence groundwaters, probably recharged in the Late Pleistocene, have acquired their elevated Cl content by dissolution of halite and dilution with meteoric water beneath the zone of active groundwater movement (Darling et al., 1997). Over most of the area, saline water with Cl up to 100 000 mg/l is present beneath the fresh water (British Geological Survey, 1989), such as at 800 m depth below Chester (Allen et al., 1997). Lucey (1987) calculated the average residence time within the saturated zone of the Cheshire basin to be of the order of 1300 years and suggested that the upper 100 m of the aquifer was the most active, with 95 per cent of modern recharge contributing to its flow and an average residence time of 275 years compared with 21 000 years for the bottom 400 m of the aquifer (Griffiths et al., 2002).

The oldest, deeper waters in the West Midlands are of Ca-Mg-SO_4 composition. There are also some higher Br/Cl and Na/Cl ratios indicating a deeper source of waters near the River Stour (Tyler-Whittle et al., 2002). Some poor-quality groundwaters in the Shropshire Permo-Triassic sandstone have also been attributed to flow of saline water from the neighbouring Salop Formation of the Warwickshire Group (Smedley et al., 2005). In the Worcester basin, around Stratford-upon-Avon, saline groundwater was found in the 200 m deep Old Rectory Borehole, Lighthorne, south of Leamington Spa, which possibly also penetrated the Salop Formation of the Warwickshire Group. Data on the chemistry of formation waters from drill-stem tests, from an interval from 936 to 942 m depth in the Wilmslow Sandstone Formation at the Kempsey Borehole, showed that the groundwater had a substantial component of Quaternary recharge (Darling et al., 1997) and water quality indicates that the aquifer system has been considerably flushed by meteoric water (Downing and Gray, 1986). It is possible that this is through direct recharge by groundwater moving down through the overlying Mercia Mudstone Group, although the relatively low salinity may indicate that this is not significant (Downing and Gray, 1986). The higher salinity of the Bridgnorth Sandstone Formation supports the suggestion that the intervening Kidderminster Formation restricts flow between the Wilmslow and Bridgnorth sandstone formations (Downing and Gray, 1986).

Groundwater age in Nottinghamshire was investigated by Andrews and Lee (1979). ^{14}C activity of dissolved HCO_3 in groundwater decreases eastwards in the confined aquifer and indicates ages of up to 3 x 10^4 years for water about 30 km from the recharge zone. High ^4He waters occur in the confined part of the aquifer (Andrews and Lee, 1979). However, excess radiogenic ^4He contents suggest ages about twice as old as the corrected ^{14}C ages; this could reflect natural variations in aquifer radio-element contents or diffusion of ^4He from the overlying Mercia Mudstone Group (Andrews and Lee, 1979). Noble gas measurements indicate that waters furthest from outcrop were recharged at temperatures on average 5–7°C lower than those at or near outcrop, during the Late Pleistocene (Andrews and Lee, 1979). There was a gap in recharge, as indicated by the gap in groundwater ages, from about 10^4 to 2 x 10^4 yr BP (Andrews and Lee, 1979). The average rate of water movement down dip, estimated using the ^{14}C ages, is about 40 cm/yr (Andrews and Lee, 1979).

6.3.1.5 ZECHSTEIN GROUP

The Zechstein Group dolomites (formerly ‘Magnesian Limestone’) comprise marine dolostone, limestone, evaporite, mudstone and siltstone (British Geological Survey, 2016). They are present in a very small area in the north-east of the region (north of Loughborough). They dip towards the east, beneath the Sherwood Sandstone Group, and overlie the Pennine Upper Coal Measures Formation and Warwickshire Group. There is one water-bearing unit in the area, the Cadeby Formation (Howard et al., 2009), a dense dolostone (Allen et al., 1997). This is generally confined by the overlying Edlington Formation, also of the Zechstein Group (Howard, et al., 2009). The permeability of this unit depends on the degree and nature of fractures within it (Allen et al., 1997) and it may have substantial transmissivities where the fracture frequency is high (Allen et al., 1997). The hydrogeological properties of this unit are discussed in the corresponding report for the adjacent Pennines region where the unit is more extensive.

6.3.1.6 PERMIAN SANDSTONES

The Permian sandstones, including the Bridgnorth Sandstone Formation and Appleby Group, comprise soft, medium-grained sandstones (British Geological Survey, 2016) with local mudstone beds and breccia. The Appleby Group, which includes the Collyhurst Sandstone Formation, is present in the Cheshire basin. However, in this region, in the south of the Cheshire basin, the group is always deeper than 1000 m and is therefore not considered further.

The Bridgnorth Sandstone Formation underlies the Sherwood Sandstone Group and typically acts as a single hydrogeological unit in the West Midlands. It overlies rocks of Carboniferous age or older and is poorly cemented and highly permeable. The dominant lithology consists of poorly indurated, friable, poorly sorted, fine to medium-grained sandstone with thin, coarser-grained layers (Allen et al., 1997).

The groundwater water in the Permian sandstone is more saline than the Triassic aquifer in the deep, in excess of 1000 m Kempsey Borehole, suggesting a restricted flow between the two aquifers (Downing and Gray, 1986). The piezometric surface was calculated to be about 20 m above ground level (Downing and Gray, 1986).

6.3.2 Hydrogeology of the Devonian and Carboniferous sedimentary cover

6.3.2.1 WARWICKSHIRE GROUP

In Warwickshire, the Allesley, Keresley and Whitacre members of the Salop Formation are considered principal aquifers. In this area, the Ashow, Kenilworth Sandstone and Tile Hill Mudstone formations lie above the Salop Formation and are also considered principal aquifers (Jones, et al., 2000).

The Warwickshire Group aquifer system is multilayered, with sandstone aquifer units separated by mudstone aquitards. It is dual porosity, with both fracture and intergranular porosity (Besian and Pearson, 2007). The upper parts of the Salop Formation are thought to be more productive than the lower parts (Jones et al., 2000). The Whitacre Member of the Salop Formation is very well cemented and groundwater movement is almost entirely via fractures. The Corley Sandstone in the Keresley Member of the Salop Formation constitutes the most important water-bearing horizon in the western part of the Warwickshire coalfield (Jones et al., 2000).

Small supplies of groundwater can be obtained from shallow wells in the Salop Formation (Whitehead et al., 1947; Earp and Taylor, 1986). However, such yields are often not sustainable because of a lack of direct recharge and the compartmentalisation of the aquifer into isolated blocks by extensive faulting and folding (British Geological Survey, 1989). Increased fracturing close to faults may enhance yields (Aitkenhead et al., 2002). Disused colliery workings provide considerable storage, and large-diameter shafts have produced high yields (British Geological Survey, 1989). Groundwater has been produced to a depth of 250 m in the sandstones of the Warwickshire Group in the Cheshire and Clwyd basins, in joints and fractures sometimes caused by mining subsidence. Mines below these depths are generally dry (British Geological Survey, 1989).

In the Wyre Forest the Warwickshire Group forms a multilayered aquifer, with interbedded sandstone aquifer units separated by mudstone aquitards (Pearson, 2008). The rocks are bounded to the east and south by rocks of Triassic age, and to the west by rocks of Devonian age. Aquifer (sandstone) units are not locally extensive and aquitard (mudstone) units are common enough that the overall vertical permeability is substantially lower than overall horizontal permeability (Pearson, 2008). Faulting is common in this area, and tends to subdivide groundwater into smaller, hydrogeologically discrete zones (Rees and Wilson, 1998; Pearson, 2008). However any increased fracturing may increase the permeability of the strata in the zone adjacent to the fault. Generally, the groundwater will tend to be contained within separate zones of permeable strata, therefore there will be many separate bodies of groundwater throughout the full depth of the Coal Measures strata (Pearson, 2008). Mining subsidence can create hydraulic continuities between water-bearing layers and in some locations between aquifer horizons and mine workings themselves (Pearson, 2008). Large quantities of water were once abstracted from the Halesowen Formation for public supply around Coventry, Nuneaton and Bedworth. However, this formation is now less important as an aquifer due to declining yields in many boreholes (Bridge et al., 1998). The argillaceous rocks of the Etruria Formation yield little or no water. However, fractures in the sandstones and conglomerates can yield moderate quantities of water suitable for small-scale use. Although these are generally well cemented, in south Staffordshire they often have a more sandy and porous matrix and may yield a good supply (Jones et al., 2000).

Groundwater quality in the Warwickshire Group is very variable, reflecting vertical stratification and the interception of water from different formations with different residence times (Besian and Pearson, 2007). Water contained within former mine workings can be expected to be highly mineralised (Pearson, 2008) and large increases in the concentrations of SO_4, Cl and Fe and methane around Stoke-on-Trent (Rees and Wilson, 1998).

6.3.2.2 CARBONIFEROUS LIMESTONE SUPERGROUP

The Carboniferous Limestone Supergroup underlies rocks of late Carboniferous age (from north to south: Craven, Millstone Grit and Warwickshire groups) and overlies rocks of Silurian age and older. It typically consists of bioclastic to micritic limestone and dolostone, and sandstone is locally common.

It is an aquifer almost entirely by virtue of the secondary network of solution-enlarged fractures. Faults may act as high or low permeability zones (Allen et al., 1997). Flow velocities can be very rapid, of the order of hundreds of metres per hour (as shown by tracer experiments) but this depends on the presence of large, interconnected conduit systems, and in regions without such systems velocities will be much slower (Allen et al., 1997). Boreholes will be productive, possibly with very high yields, if they intersect conduits and non-productive if they fail to do so (Jones et al., 2000). Consequently, failure to intersect water-bearing fractures in the limestones often results in very low yielding or dry boreholes (Jones et al., 2000). The 1006 m deep Barkestone No. 1 Borehole (between Nottingham and Grantham) terminated in Carboniferous limestone. It had an artesian flow at a pressure head of 1090 m, equivalent to a piezometric level as much as 84 m above ground.

Total dissolved solids in the Carboniferous limestone increases with depth (Downing and Howitt, 1968), and from about 1000 mg/l around Nottingham, to about 7000 mg/l between Newark and east of Grantham (increasing eastwards from the Pennine outcrop). The saline waters of the Carboniferous rocks in the East Midlands are thought to be Carboniferous in age and result from the diagenesis of these waters (Downing and Howitt, 1968).

6.3.3 Hydrogeology of the basement rocks and igneous intrusions

There is no hydrogeological information for these units in the reviewed literature for this region, with minor exceptions. In the Lichfield area, Cambrian igneous rocks have historically been reported to yield enough groundwater from shallow fracture systems to support small domestic supplies (Barrow et al., 1919). Precambrian rocks in the Coalville district may yield small supplies of groundwater, which is restricted to joints and fractures. In Charnwood Forest a shallow (14 m) borehole in Neoproterozoic rocks produced small yields (Worssam and Old, 1988). A spring issues from these rocks at Longden Manor, south of Shrewsbury, but a trial boring was unsuccessful (Pocock et al., 1938).

6.4 EVIDENCE FOR CONNECTION BETWEEN GROUNDWATER SYSTEMS

6.4.1 Separation of aquifers

The Mercia Mudstone Group may confine the Permo-Triassic aquifers across the region, and, in the Worcester basin, the higher salinity of the Permian Bridgnorth Sandstone Formation is consistent with the inference that the intervening Kidderminster Formation restricts flow between the Triassic Wilmslow Formation and Bridgnorth Sandstone Formation (Downing and Gray, 1986). Where it is not fractured, the well-cemented Chester Formation may act as an aquitard between the other Triassic sandstone units above and the Permian sandstone below it (Allen et al., 1997; Barclay et al., 1997). For example, a head difference of 20 m is sustained north of Redditch (Old et al., 1991).

In addition, there is evidence for multiple hydraulic separations within units. For example, in the Warwickshire Group the aquifer system is described as ‘multilayered’ with sandstone aquifer units separated by mudstone aquitards (Besian and Pearson, 2007). In the West Midlands and Shropshire, fine-grained horizons can give rise to locally confined conditions (Allen et al., 1997) and can cause hydraulic stratification, resulting in double or multiple aquifer systems (Allen et al., 1997).

6.4.2 Geological pathways

Flashes (lakes) are developed in salt karst in Cheshire, leading to natural subsidence features. The subsidence has been accelerated in some areas following brine abstraction. Karstification is enhanced along local zones of enhanced groundwater flow, known as brine streams or ‘runs’, which occur at the rockhead, usually at depths of 50 to 120 m and were accelerated where brine was pumped (Waltham et al., 1997).

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. For example, the Cheshire basin is bound by synsedimentary extensional faults and the major features within the basins are large, generally north–south or north-west to south-east-trending, normal faults with throws of up to 300 m (e.g. Wem–Red Rock) (Allen et al., 1998). However, generally the effects of faults are more local. 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. An example of fault-controlled springs can be found in the Shrewsbury area, where springs along the line of the Church Stretton Fault afford small supplies and there is a line of springs along the faulted ground on the western slopes of The Lawley hill and the Cardeston Fault (Pocock et al., 1938).

There are no documented thermal springs (>15°C) in the area.

6.4.3 Anthropogenic features

There are high densities of boreholes greater than 200 m in depth in the region, particularly in the centre, around Birmingham and Coventry, through Stafford and Stoke-on-Trent and towards Northwich, and in an area between Tamworth, Nottingham and Grantham (see Section 8.2). However, their influence, if any, on regional groundwater flows and heads is undocumented in the literature reviewed.

The closure of coal mines across the region during the second part of the twentieth century and the cessation of dewatering have contributed to a rise in groundwater levels, for example in Telford and Wolverhampton. Currently, levels are now believed to be at, or close to, those that existed prior to mining operations (Bridge and Hough, 2002). Groundwater levels are rising within the mining areas of the north-west Leicestershire and south Derbyshire coalfields, which has possibly caused localised subsidence (Carney et al., 2001).

Evaporite mines (in the Mercia Mudstone Group) greater than 100 m in depth are present around Loughborough, Burton-on-Trent and Stafford, and between Crewe and Northwich (described in section 8.4). Rock-salt was mined and then brine extracted from the Droitwich and Stoke Prior areas in the south-west of the region (Mitchell et al., 1961). Brine is also extracted from the Cheshire brine fields by controlled solution-mining methods. Surface subsidence occurs as a result of rock-salt mining in Stafford, Stoke-on-Trent, Droitwich and Cheshire. Wild brining (the uncontrolled pumping of brines) has caused problems in Cheshire in the past (Rees and Wilson, 1998). Mining-induced subsidence fractures are present in the bed of the Rising Brook, a low-flow stream in Cannock Chase where flow losses occur over very short intervals, rather than uniformly along its length (Allen et al., 1998). Disused colliery workings provide considerable storage, and large-diameter shafts have yielded over 80 l/s (British Geological Survey, 1989).

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

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

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

- glacial 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 as far south as the London area (Figure 20; RWM 2016a; 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 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.

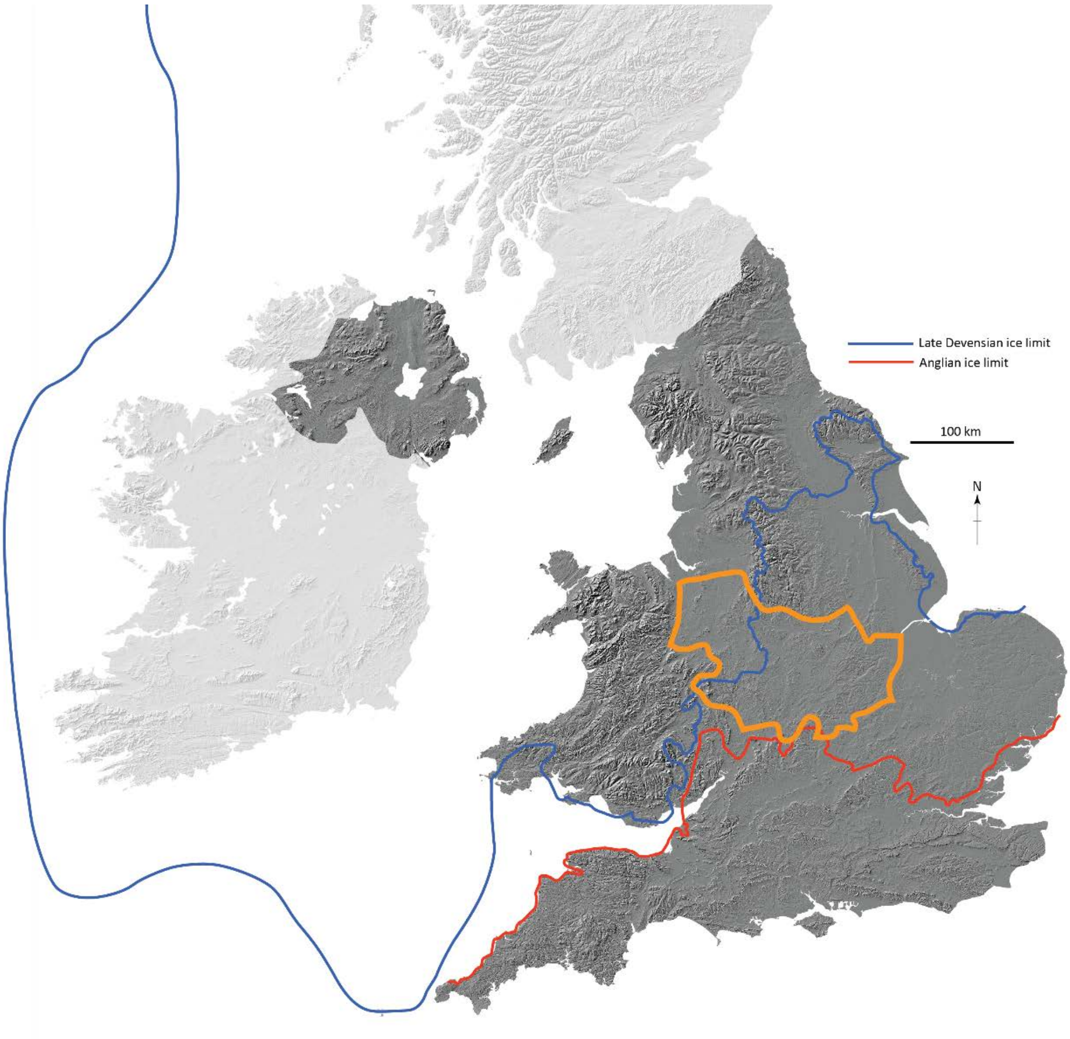


Figure 20 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and late Devensian (around 30 to 16 ka). The location of the Central England region is delineated by the orange line. Produced using Copernicus data and information funded by the European Union – EU-DEM layers © EEA.

7.2.2 A regional perspective

Geological evidence demonstrates that Central England has only been glaciated directly during large continental-scale glaciations over the past two and a half million years (Quaternary Period; see Figure 20; RWM, 2016a; Clark et al., 2004). The region could also have been glaciated by Welsh ice during lowland glaciation although evidence would likely have been eroded during subsequent larger glaciations. Based upon geological evidence and the premise that the recent geological record provides a worst-case analogue for the future, the region may infrequently undergo periods of lowland and continental-scale glaciation over the next million years (RWM, 2016b). Important natural processes that may affect the depth range of interest include the incision of tunnel valleys by fast-flowing meltwater streams that occur beneath the glacier (RWM, 2016b). This may produce localised erosion over several phases of glaciation to depths beyond 200 m (RWM, 2016b). The region may also be affected by isostatic rebound and/or a glacier forebulge relating to the glaciation of an adjacent onshore (e.g. Wales) or offshore (e.g. North Sea, Irish Sea (RWM, 2016b)) region. This may result in increased fracturing and fault reactivation within the subsurface leading to enhanced seismicity (RWM, 2016b). The proximity of the north-west of the Central England region to present coastal areas makes the region susceptible to local 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).

7.3 PERMAFROST

7.3.1 A UK-scale context

Permafrost (frozen ground) occurs when the temperature of the ground remains below 0°C for at least two consecutive years (French, 2007). Permafrost, therefore, develops where average air temperatures are much colder than the present day and consequently there is potential for significant thicknesses of permafrost to develop over decadal to centennial timescales (Busby et al., 2014). It is also important to note that permafrost and glaciation are not synonymous. Whilst many glaciated areas are subjected to periglacial processes, not all areas affected by permafrost will become glaciated. For example, areas situated to the south of the major limits of glaciation in the UK (see Figure 20) 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 Central England will be subjected to the development of permafrost, which may extend to a few hundred metres below NGS datum (Shaw et al., 2012; Busby et al., 2014). The development of permafrost can affect groundwater chemistry and behaviour (Shaw et al., 2012).

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 21). 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 21). 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).

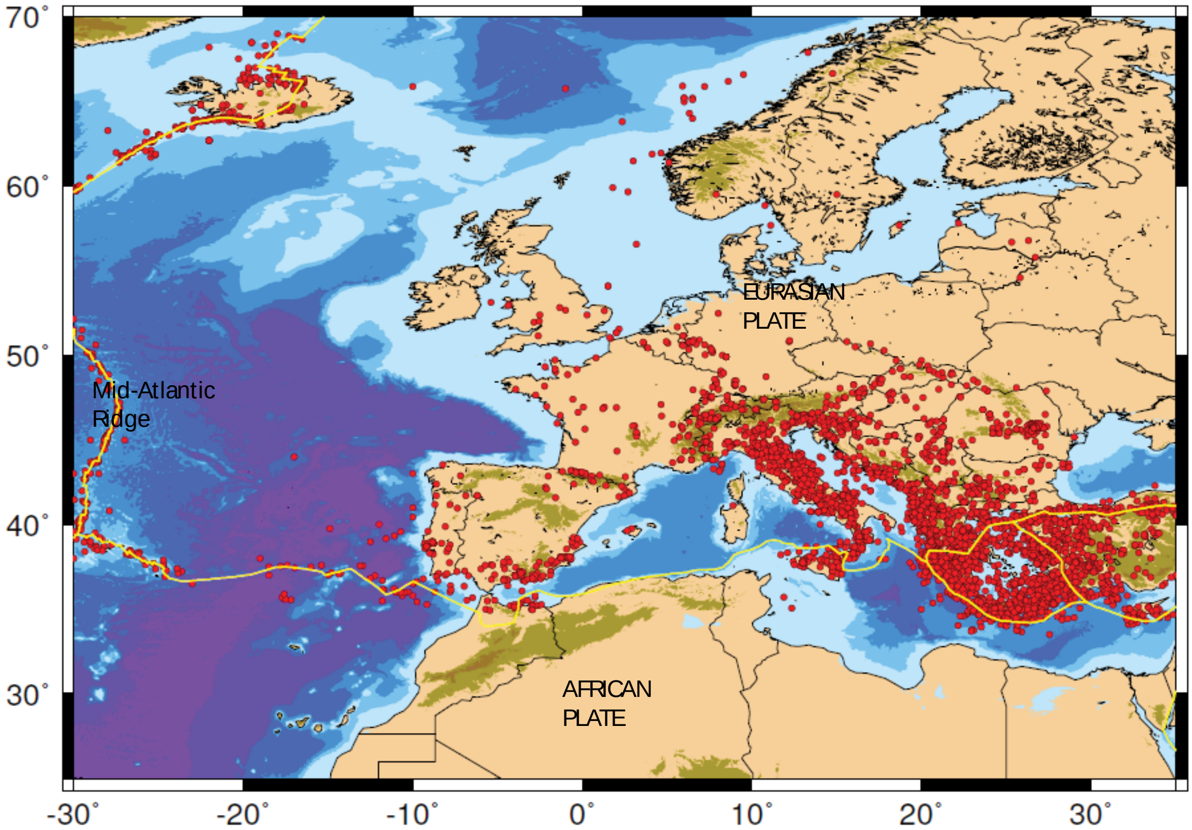


Figure 21 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

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). Therefore for compatibility with the standard practice in seismic hazard assessment, the ML values have been converted to Mw, using the equation from Grünthal et al. (2009):

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

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

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

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

A requirement for any statistical analysis of seismicity is that one needs to know the extent to which the record of main shocks in an earthquake catalogue is complete. For example, some historic earthquakes that happened may not be present in the catalogue because no record of them survives to the present day. Normally, completeness improves with time (better nearer the present day) and also with magnitude (better for larger earthquakes). Thus one can describe a series of time intervals within which it is considered that the catalogue definitely contains all earthquakes above a certain magnitude threshold. This threshold value can be defined as the lowest magnitude at which 100 per cent of the earthquakes in a space-time volume are detected (Rydelek and Sacks, 1989). Therefore it is usually low for recent seismicity and gets progressively higher back in time. For this study we use the completeness estimates for the UK catalogue determined by Musson and Sargeant (2007), which are shown in Table 4. 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 4 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 22 shows a map of all of the main hocks 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 (Figure 22).

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 22), 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).

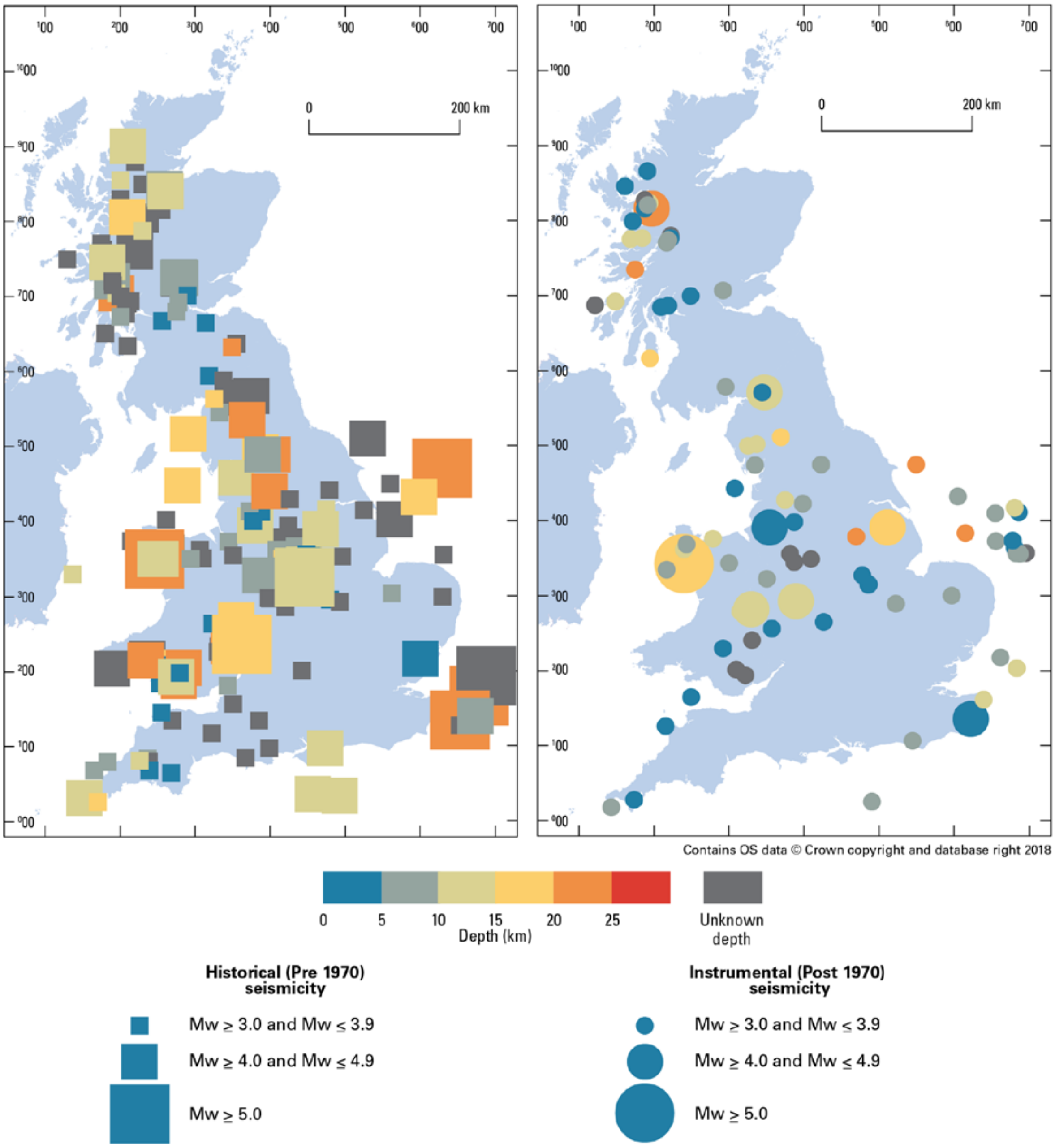


Figure 22 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological 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 23 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 (Figure 23).

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.

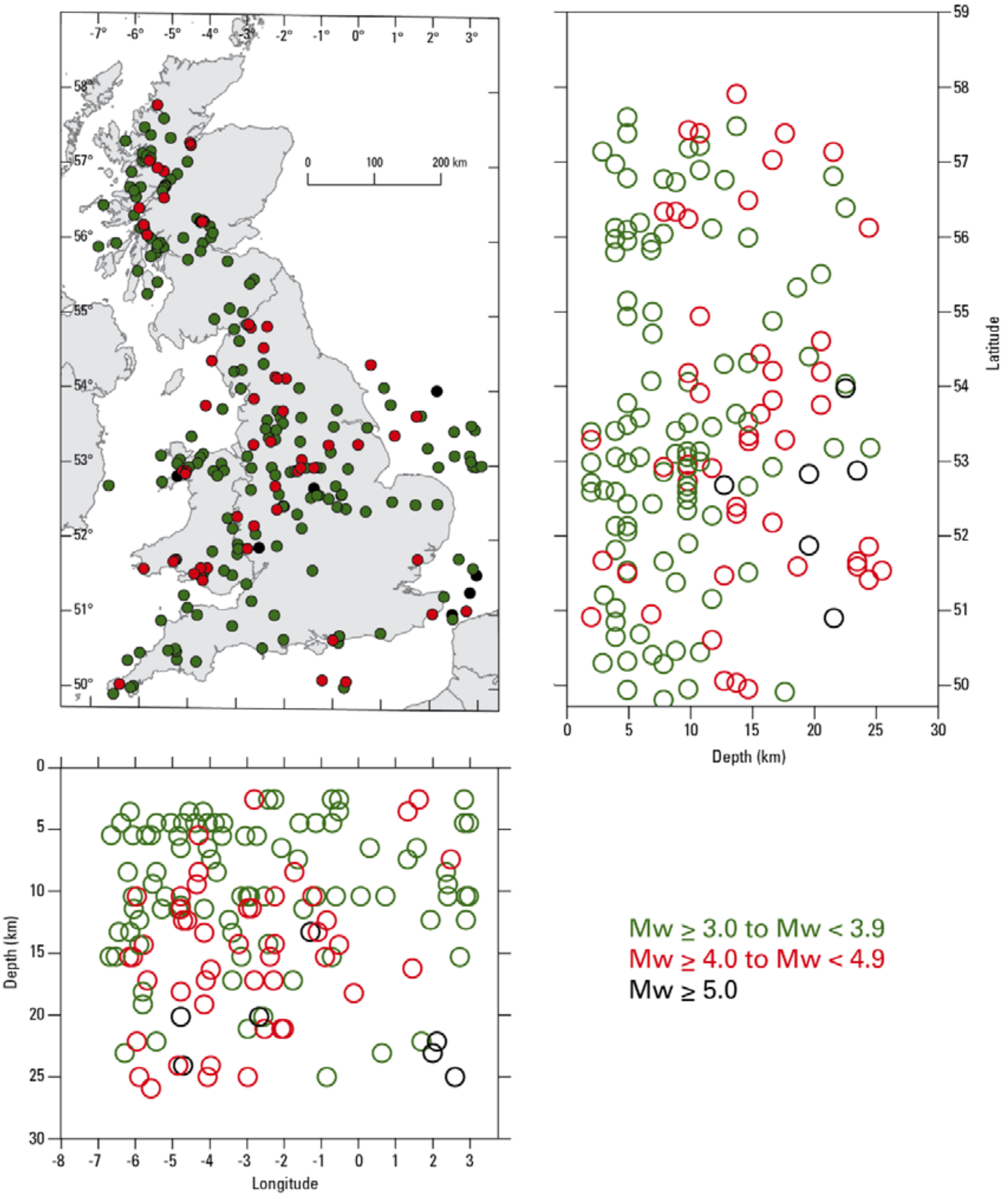


Figure 23 Relationship between the focal depth and the geographical distribution of the mains shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

7.4.4 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 4) and computes a 5 x 5 matrix of possible values of a and b along with associated uncertainties while also taking into account the correlation between them.

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

7.4.6 Impact of future glaciation

The possibility of renewed glaciation in the next ten thousand years means that estimates of the distribution and rates of regional seismicity cannot be considered the same as they are now. Geological investigations in a number of regions have found evidence for significant postglacial movement of large neotectonic fault systems, which were likely to have produced large earthquakes around the end-glacial period. For example, Lagerbäck (1979) suggests that the 150 km long, 13 m high fault scarp of the Pårve Fault in Sweden was caused by a series of postglacial earthquakes. Adams (1996) finds evidence for postglacial thrust faults in eastern Canada. Davenport et al. (1989) and Ringrose et al. (1991) find similar evidence for significant postglacial fault displacements in Scotland. However, Firth and Stewart (2000) argues 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 24 shows earthquake activity in the Central England region. Three earthquakes with magnitude of Mw 4.0 or greater have been observed in this region in the last 130 years. The largest of these was a magnitude 5 Mw earthquake in 1957, which was one of the most damaging earthquakes to occur in Britain in the 20th Century. The epicentre was near Castle Donington, about 10 km south-east of Derby and there was widespread damage to chimneys and roofs in and around Derby, Nottingham and Loughborough (Musson, 1994). A few people were hurt by falling masonry. The earthquake caused damage to Blackbrook reservoir, making this one of the three British earthquakes to have caused damage to a reservoir, the other two being the 1839 (Mw 4.5) Comrie and 1979 (Mw 3.0) Ochil Hills earthquakes (Musson, 2007). An inspection of the Blackbrook reservoir was undertaken after the 1957 earthquake. It was seen that all the coping stones were lifted, the dam appeared to have been lifted bodily and then fallen back, and a few cracks appeared in the dam but later closed up (Labrum, 1994).

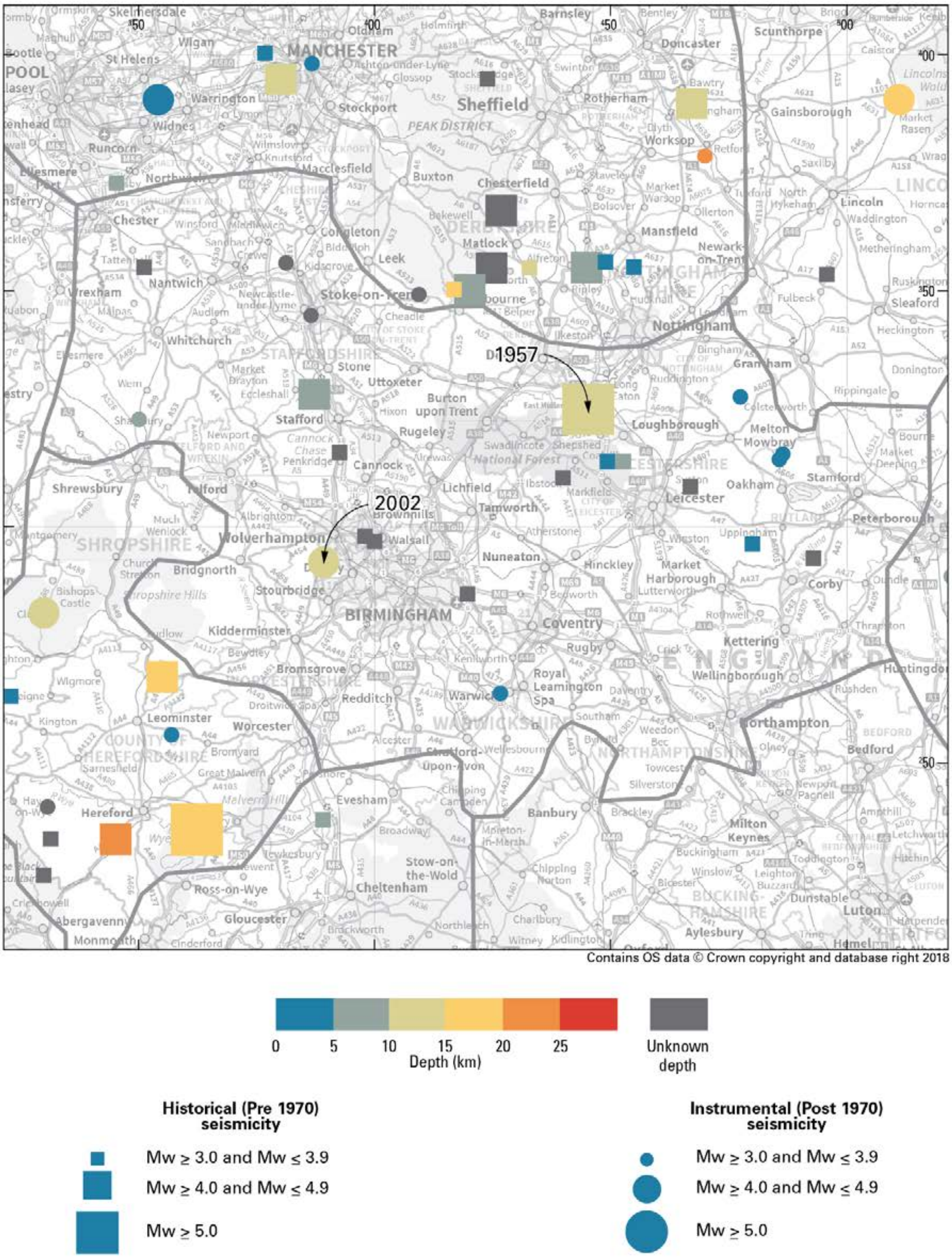


Figure 24 Historical and instrumentally recorded earthquakes in the Central England region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

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

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

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

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

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

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

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

8.2 OVERVIEW OF RESOURCES IN THE REGION

Figure 25 shows the distribution of mineral resources in the Central England region. The region contains extensive coalfields that have in part been mined. Both the Staffordshire and Warwickshire coalfields were important sources of deep-mined coal. There are several oil and gas fields and areas of the region are prospective for shale oil and gas. Salt, gypsum and anhydrite have been exploited in the region and, in the north-west, salt caverns have been developed for gas storage purposes.

8.3 COAL AND RELATED COMMODITIES

A large part of the region is underlain by deep coal seams (up to 1200 m below NGS datum) with parts of the north-west of the region underlain by very deep coal seams (greater than 1200 m below NGS datum) (Figure 27). While the deep coal seams have been extensively worked in the past there are currently no operating coal mines. Large areas of the coal remain unworked.

Coal has been worked by deep mining in the Staffordshire coalfield since the Middle Ages, peak production being in the middle of the 19th century. Around Staffordshire, the coalfield has an unusually thick coal-bearing sequence, but the seams exhibit high angles of dip almost everywhere. The area has had a long history of coal mining, much of the coal being consumed locally. With the decline in use of coal for domestic and industrial applications from about 1950, the major market became electricity generation, but this too has declined markedly in recent years with a consequent decline in the number of collieries. The last two British Coal deep mines, Silverdale and Trentham, which worked seams in the southern, concealed part of the coalfield where the seams are less geologically disturbed, closed in the 1990s. In south Staffordshire, the last deep mine (Baggeridge Colliery near Dudley) closed in 1968. Further deep mining is unlikely.

In the Warwickshire coalfield, deep mining really only began in the second half of the 19th century. Output reached its highest level in 1939 when 5.8 million tonnes were produced from 20 mines. Since 1947, when the coal mining industry was nationalised, closures and mergers progressively reduced the number of pits. With the closure of Coventry Colliery in 1996, Daw Mill remained the last operating deep mine until 2013, when it was closed following an underground fire.

The southernmost extent of the Nottinghamshire coalfield also extends into this region. The deep mines of Cotgrave and Clifton worked coal at depth. Deep coal resources were also worked at Asfordby Colliery near to Melton Mowbray in Leicestershire.

There are licences for abandoned mine methane in the region, for the closed Hem Heath and Florence collieries.

There are no current licences for extraction of coal-bed methane, coal-mine methane or coal gasification in any of the coalfield areas, but exploration has taken place for coal-bed methane in the Warwickshire, Staffordshire and concealed Cannock coalfields. Measured average methane values of the coals in this region are low and there is considered to be little potential for resources. There has been some investigation into the potential for underground coal gasification of the unworked deep coal resources around Stoke and Warwick; a licence was granted but was subsequently relinquished by the operator because of public opposition.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

There are extensive deposits of salt, gypsum and anhydrite in the region. These have been exploited in several areas (Figure 25). Gypsum is mined near Barrow-upon-Soar at 170 m below NGS datum and there are also extensive mines at East Leake and Gotham, however, these are at much shallower depths, 20 to 30 m, below NGS datum. Anhydrite/gypsum is also mined at Fauld, currently to a maximum depth of 100 m below NGS datum.

Extensive salt resources underlie the north-west of the region between Wem and Macclesfield, around Stafford and Uttoxeter, and south of Bromsgrove.

Salt has been mined in the Winsford/Nantwich areas, and has been extracted near Stafford and Droitwich, by conventional, solution and wild-brining methods. Two major salt formations, the Northwich Halite Member and the Wilkesley Halite Member, occur extensively in the Cheshire basin, though production is entirely confined to the former. The maximum known thickness of the Northwich Halite Member is about 280 m and the salt occurs in beds of virtually pure halite and in others where there are varying amounts of mudstone and siltstone. It has been estimated that some 25 per cent consists of mudstone. The Wilkesley Halite Member is even thicker and has a known thickness of up to about 405 m. The upper half of the Wilkesley Halite Member is purer than the Northwich Halite Member.

Salt was produced from brine springs in Staffordshire at least as early as the 17th century and, in 1893, an industry was established at Stafford Common following the discovery of rock-salt in boreholes in 1891. Production of salt in Stafford by natural brine pumping ceased in 1970 because of subsidence problems. To the east, brine wells have been recorded at Weston-on-Trent and Shirleywich but the production of salt ceased there in 1901. The subsurface extent of the Stafford Halite Member is imprecisely known but it appears to be of low quality and very thin at the margins.

Winsford Salt Mine, which is worked by pillar and stall methods, underlies a large area north-east of Winsford, reaching a maximum depth of 200 m below NGS datum. The rock-salt, which contains about 92 per cent salt, is principally used for de-icing roads. The mine, with some 26 million m^3 of space, has a constant temperature and humidity and is dry and gas free, and has several past mining applications. Part of the mine is currently being used as secure document storage and part of the mine is being used for the permanent storage of hazardous wastes. Strict criteria are applied to the type of material stored, which is dry waste that is nonflammable, nonbiodegradable and nonradioactive.

Brine pumping covers extensive areas between Sandbach and Middlewich and to the east of Nantwich as well as underneath Stafford. Depths affected by this method of extraction can extend to 500 m. Controlled brine pumping involves the creation of stable cavities, up to 145 m in diameter and up to 200 m in height, in suitable salt strata by introducing water under carefully controlled conditions and pumping up the resultant brine. The size and shape of the cavities are designed to maintain stability of the overlying strata. Brine wells are drilled on a regular grid about 200 m apart and the process recovers about 25 per cent of the total salt reserve. Controlled brine pumping takes place at the Holford and Warmingham brine fields in Cheshire, from the Northwich Halite Member at depths of over 200 m below NGS datum.

Completed solution cavities are left full of saturated brine, although some are used for both waste disposal and storage purposes. Salt-bearing strata are ideally suited for the creation of storage cavities for natural gas, compressed air and fluids. In particular there is increasing interest in the creation of smaller cavities for natural gas storage. This is taking place at the Warmingham brine field and at the Holford brine field.

In the south of the region, rock salt underlies an area of at least 50 km^2 to the north-east of Worcester. Droitwich has been famous for its brine springs for many centuries and these may have provided the reason for siting the town, probably in pre-Roman times. The town became a salt manufacturing centre with a peak output of 122 000 tonnes in 1872–73. Stoke Prior subsequently supplanted Droitwich as the focus of salt production. Rock-salt was discovered at Stoke Prior in 1828 and was mined for a time until the workings flooded. The industry was re-established with natural brine pumping and continued until 1972 when the operations were terminated because of subsidence problems. Output during the latter years of operation was some 150 000 tonnes a year.

Cavities have been mined by solutional mining methods in the north-west of the region for gas storage purposes.

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. Bedded Jurassic iron ores have been mined to the south-west of Northampton; in the Kettering and Corby area; at Grantham, and at Eaton. Iron ore extraction in all these areas was from open pit working or from underground mines at shallow depths of less than 100 m below NGS datum. A number of other commodities, including limestone and slate, have also been mined at shallow depths in the region.

8.6 VEIN-TYPE AND RELATED ORE DEPOSITS

There are a few small scattered vein-type ore deposits in the north of the region, none of which has been exploited at depth. The best known of these is at Alderley Edge, where extraction of copper, lead and cobalt has occurred in the past.

The orefields depicted on Figure 25 delineate the areas where most of the known mineralisation is located. However, large parts of the orefield areas 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, they may be re-examined in future for mineral resources. 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.

8.7 HYDROCARBONS (OIL AND GAS)

The West Midlands and Herefordshire and Worcestershire have a relatively low potential for the discovery of oil and gas. Within the area, the Coal Measures have the highest potential as source rocks for gas. Despite this, extensive drilling for coal in the north has not revealed any significant oil and gas finds. The best prospects for oil and gas are likely to be in south-west Warwickshire, where seismic survey data indicate that Coal Measures could be concealed at depth in the area around Barford and Stratford-upon-Avon.

Hydrocarbon shows have been recorded in several boreholes around Staffordshire, mainly in the Coal Measures Group and Carboniferous sandstones. Most of the shows are in two areas: on the north–western side of the Potteries coalfield and the area around Coalport just to the south-west of the Staffordshire county boundary. The Coalport Tar Tunnel was a small oilfield mined in the 18th century. Additionally, oil shows have been recorded in Mear Hay, Longton (5 barrels/day in 1874), Fair Lady, Hem Heath, Mossfield and Walsall Wood collieries. Oil sands (shows at the surface) are recorded in road cuttings at Burton and Dane, however, despite several wells, no economic accumulations of oil or gas have been discovered.

In the Cheshire basin the latest exploration was confined to Triassic reservoirs, although exploration of Carboniferous rocks has been advocated. The potential for the discovery of economic accumulations of conventional hydrocarbons is reduced because there appears to be a lack of significant volumes of mature source rocks.

There is a gas field north-west of Biddulph, Nooks Farm, in the north-west of the region where drilling has taken place but site development has yet to commence. There are also scattered small oilfields in the north-east of the region around Cropwell Butler, Belvoir, Kinoulton and Long Clawson, of which only Long Clawson is currently operating. Gas has also been found in wells at Langar and Plungar but in subeconomic quantities.

Areas of the north-west and north-east of the region contain mudstones that have been identified as having potential for shale oil and/or gas prospectivity. Several DECC PEDL licences have been taken out between Derby, Loughborough and Grantham, and between Stoke and Nantwich (Figure 25).

8.8 GAS STORAGE

Underground gas-storage facilities are operational or under construction in the northern reaches of the Cheshire basin, in the north-west of the region around Northwich and Middlewich. The storage facilities use caverns solution mined from massively bedded Triassic halites, in particular the Northwich Halite Member. The first facility, utilising a former brine cavern developed for gas storage in the Holford brine field, has been operational since 1984. Other operational facilities are the Holford H165 cavern, Hole House (four caverns) and the Hilltop Farm extension (10 caverns), Holford (formerly Byley: eight caverns) and Stublach, which is consented for up to 24 caverns and due to be fully operational during 2018. The caverns are developed at depths between about 300 and 700 m below NGS datum. A further salt cavern storage facility adjacent to the operational Holford facility and involving up to 19 caverns is currently going through planning application and early design stages.

Whilst there were assessments during the 1960s for town gas storage in porous rocks at locations in the east of the region, notably around Nene and Stamford, there seems little immediate prospect for gas storage elsewhere in the region beyond the salt-bearing strata of the Cheshire basin.

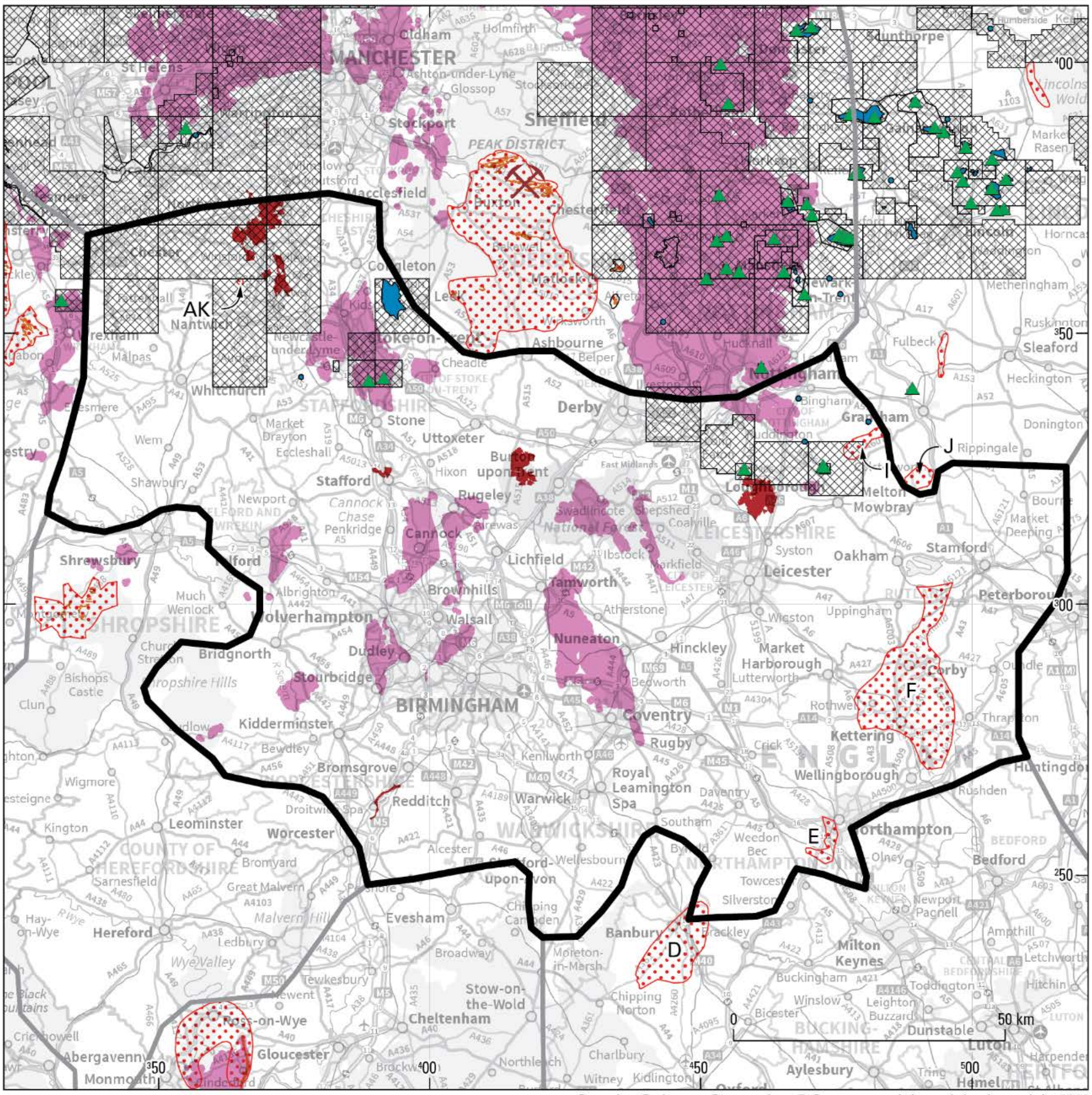
8.9 GEOTHERMAL ENERGY

Central England is underlain in the 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 areas of the basin, the basal Permian sandstones could reach up to 4500 m depth, and could potentially reach 100^{o}C at its base, with the base of the Sherwood Sandstone Group in excess of 80^{o}C. Although not nationally significant, the area has potential for local, low-enthalpy heating schemes.

Locally there is the potential for minor district heating schemes using ground-sourced heat pumps in abandoned mine workings in the various coalfields across the region. However, as yet there have been no schemes implemented.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are large clusters of deep (in excess of 200 m below NGS datum) boreholes in the region (Figure 26). These have mainly been drilled for the evaluation of the coalfield areas, oil and gas exploration and exploitation, for the evaluation and exploitation of salt deposits and for the construction of gas storage caverns.



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Central England and adjoining areas

Metal prospects

Areas of known mining over 100 m below NGS datum

Metallic and vein minerals

Evaporite minerals

Coal

Orefields

Oil and gas

Active oil and gas extraction sites

Hydrocarbon licences (as at July 2018)

Oil and gas fields

Orefield	Map label
Oxfordshire	D
Northampton	E
Corby	F
Alderly Edge	AK
Eaton	I
Grantham	J

Figure 25 The distribution of mineral resources in the Central England region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields and underground gas storage licence areas are not shown. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

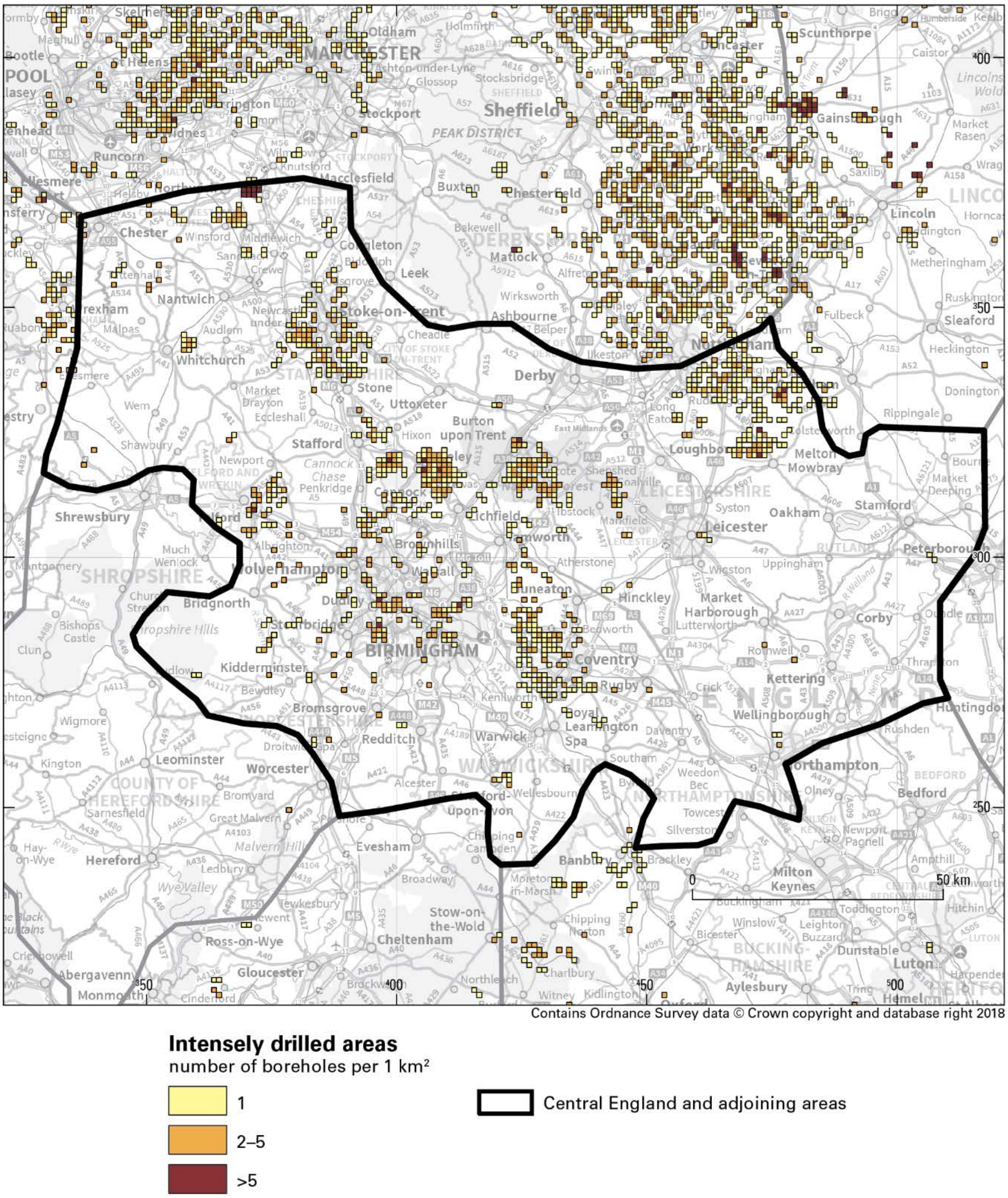

Figure 26 The location of intensely drilled areas in the Central England region, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

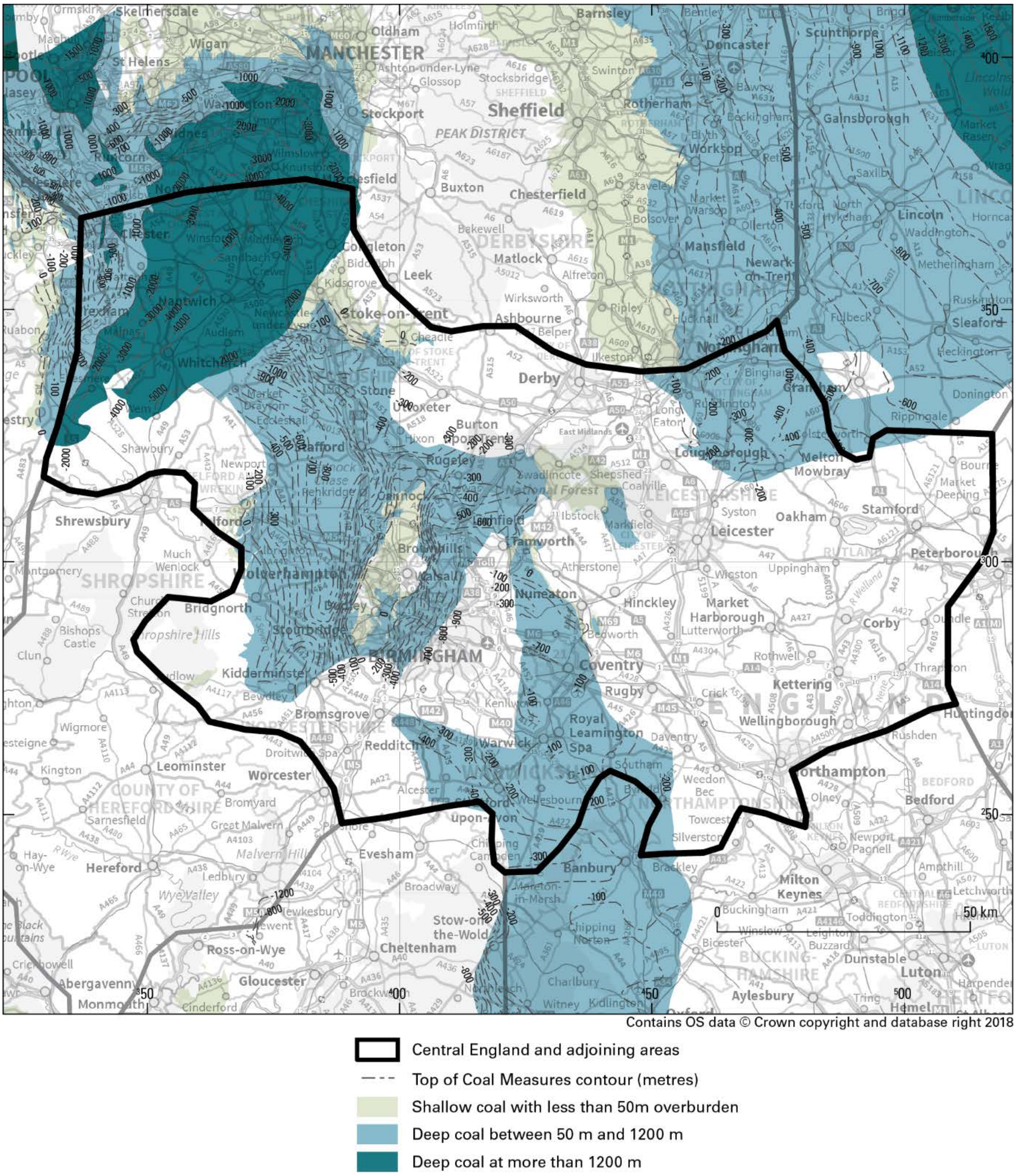

Figure 27 The distribution of coal resources in the Central England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

8.11 SUPPORTING INFORMATION

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

8.11.1 Mine depths

Reported mine depths are commonly difficult to attribute to specific datums. 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 detailed examination of historic mine plans and records, would be required to overcome this. A pragmatic solution to this issue has been to assume that reported depths are to the bottom of the deepest adit unless otherwise stated. Adits were driven from nearby valleys and another reasonable assumption is that adit level is approximately equal to NGS datum at the mine site.

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

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

Most mine shaft depths in historic mines 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 commonly a degree of uncertainty about actual depths of shafts. Where more than one depth is quoted the greatest 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 25 have been depicted where possible by applying a 100 m wide buffer to the mapped extent of the mineral vein. Where this is not possible, a 100 m buffer has been applied the location of known mines in order to encompass the possible extent of the workings. This approach ensures that any inaccuracies in the mapped vein locations and extent of past workings fall within the boundary of the area identified.

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

8.11.3 Potash, halite, gypsum, anhydrite and polyhalite deposits

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

8.11.4 Hydrocarbons (oil and gas)

The hydrocarbon fields displayed in Figure 25 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 in Figure 25 represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place.

The approach adopted for exploration and the detailed evaluation of hydrocarbon resources prior to and during exploitation has resulted in the location, extent and depth of conventional hydrocarbon reservoirs being very well constrained. Conversely, the extents, depths and contained resource of unconventional (shale) gas and oil deposits is less well constrained. The distribution of the prospective rock types is based on geological factors (see Section 4 for discussion on these) and the potential of this type of deposit in any particular location is dependent on a number of factors such as past burial depth, organic content of the rocks and the practicality of extraction, none of which have been evaluated in the region.

8.11.5 Coal and related commodities

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

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

8.11.6 Borehole depths

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

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

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

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Coal resources

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Locations of deep evaporite mines are from mine plans and BGS records. Other information on deep mineral resources has been taken from BGS mineral resources maps for England (http://www.bgs.ac.uk/mineralsuk/planning/resource.html#MRM) and the BGS BRITPITS database of mines and quarries.

Borehole locations

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Geothermal energy resources

Information for geothermal energy resources in this region has been sourced from:

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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/