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National Geological Screening: Eastern England region

Minerals and Waste Programme

Commissioned Report CR/17/092

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/092

National Geological Screening: Eastern 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 Eastern England region to underpin the process of national geological screening set out in the UK's government White Paper *Implementing geological disposal: a framework for the long-term management of higher activity radioactive waste* (DECC, 2014). The report describes geological features relevant to the safety requirements of a geological disposal facility (GDF) for radioactive waste emplaced onshore and up to 20 km offshore at depths between 200 m 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.

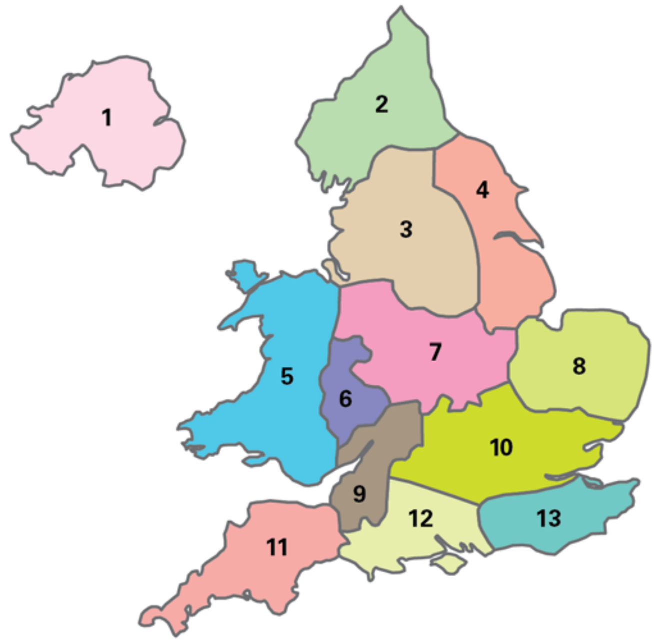
Principal aquifer — a regionally important aquifer defined by the Environment Agency as layers of rock that have high intergranular and/or fracture permeability, meaning they usually provide a high level of water storage (Environment Agency, 2013).

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 Eastern 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

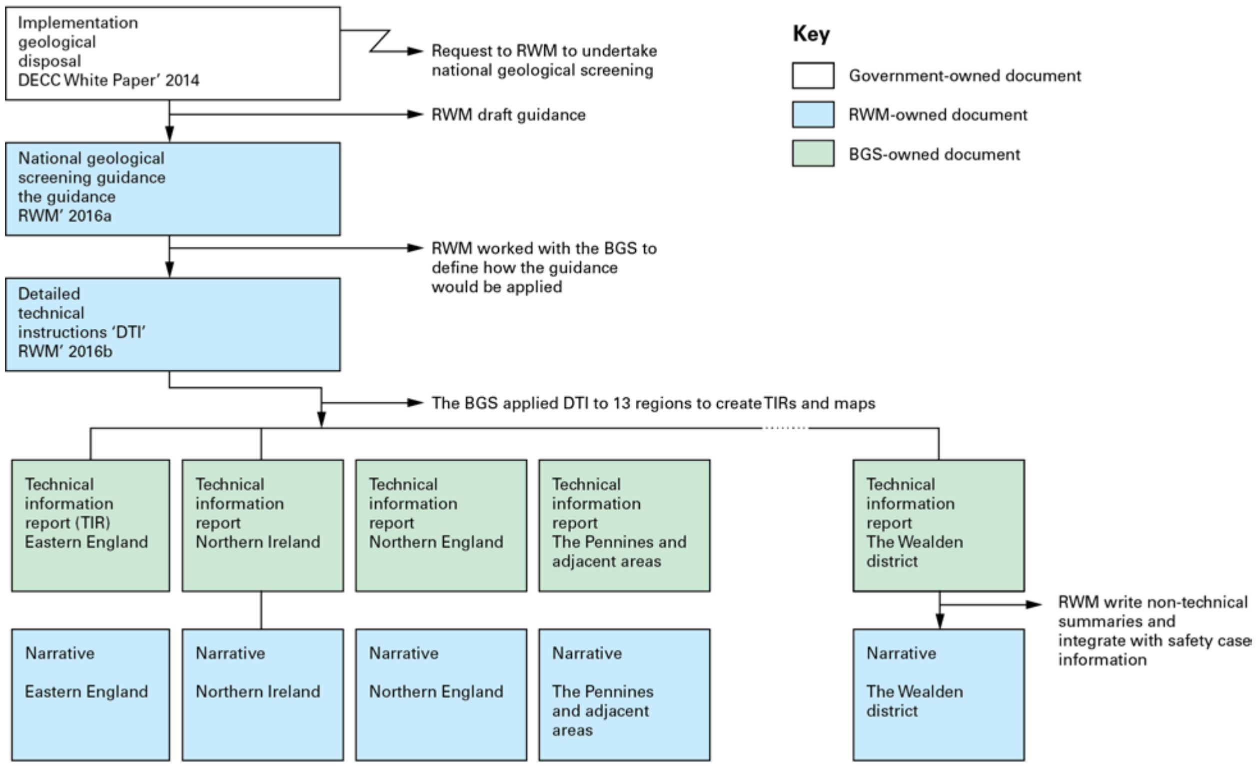


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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 km2)

3 The Eastern England region

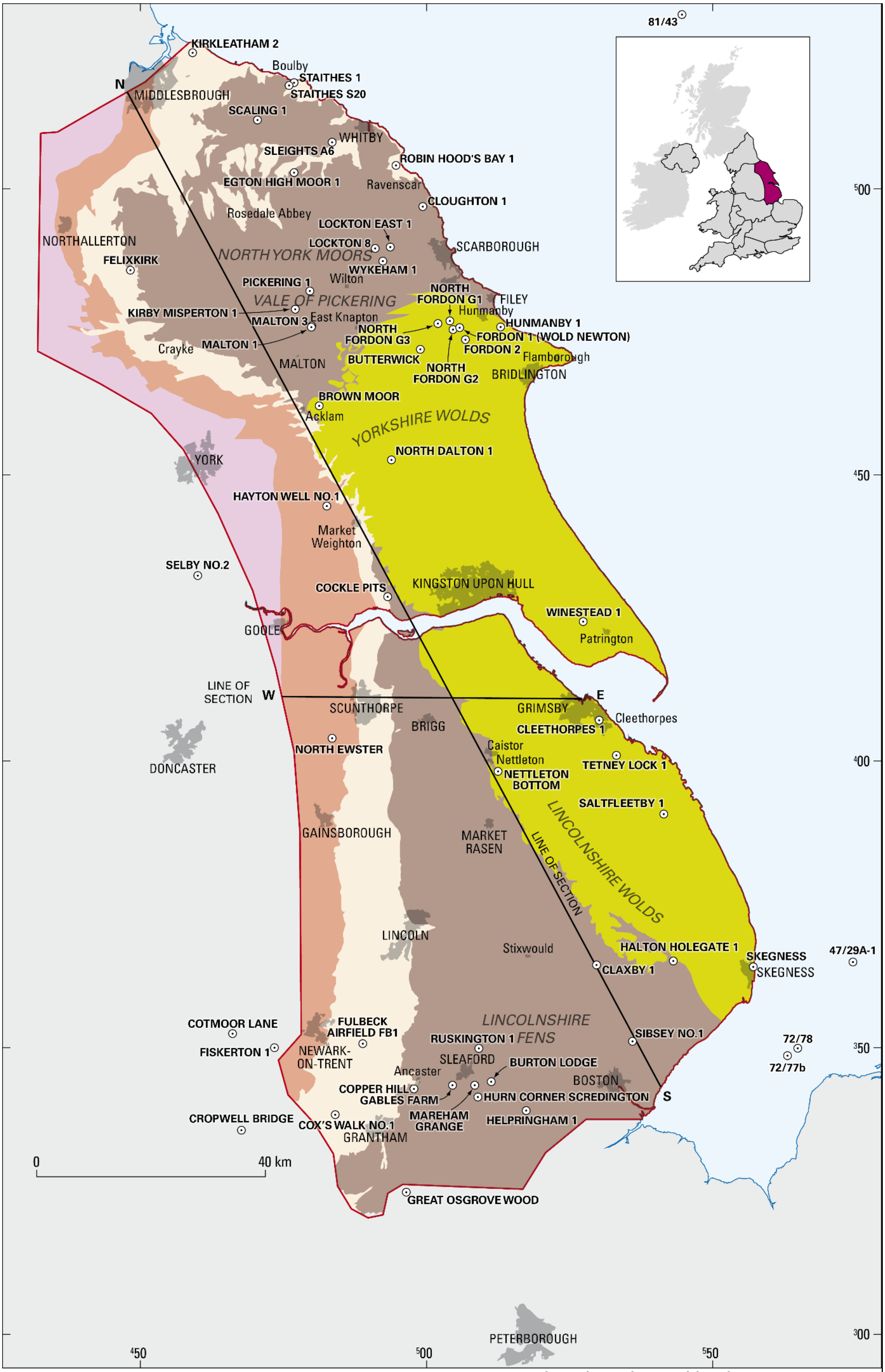
The Eastern England region covers the area between the River Tees and The Wash. It has an arbitrary western boundary running southwards along the Vale of York and the Trent valley to Grantham, and then eastwards to Boston (Figure 3). It encompasses large parts of southern Cleveland, north-east Yorkshire, Humberside, Lincolnshire and the eastern margin of Nottinghamshire.

The diverse landscape of the region reflects the underlying bedrock geology. This comprises low-lying clay plains, ridges of harder limestone and the higher ground of the Lincolnshire and Yorkshire Wolds. Upland areas are confined to the north of the region and include the Howardian and Hambleton Hills and the North York Moors (Figure 3).

The geology of the region is well known from geological and geophysical surveys. At the surface, the rocks are commonly exposed in natural outcrops and quarries, whilst at depth our knowledge is derived from mine plans and boreholes, many of the latter drilled for mineral resources and groundwater. Over 690 boreholes in the region reach a depth of 1000 m or more; this information is supplemented by geophysical surveys (seismic, gravity and magnetic) that provide general information on the rocks and structure at depth. 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. The region is underlain by thick strata of sedimentary rocks ranging in age from younger sedimentary rocks (Cretaceous, Jurassic, Triassic and Permian) to older sedimentary rocks (Carboniferous) (see legend Figure 3). Buried beneath the thick sedimentary strata are Caledonide basement rocks, the nature of which is poorly known as they are encountered in relatively few boreholes located in the south of the region. Exploration surveys, including land-based and airborne geophysical surveys, provide information on the geology at depth. Figures 4 and 5 illustrate the geological variation across the region. The reader is referred to the regional summary on the BGS website (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html) for a non-technical overview of the geology of the region and to national geological screening: Appendix A (Pharaoh and Haslam, 2018) for an account of the formation and structure of the basement, and the older and younger cover rocks of the UK. Principal structural elements of the region are shown in Figure 6.


81/43
KIRKLEATHAM 2
Boulby
STAITHES 1
STAITHES S20
N
MIDDLESBROUGH
SCALING 1
WHITBY
SLEIGHTS A6
ROBIN HOOD'S BAY 1
EGTON HIGH MOOR 1
Ravenscar
CLOUGHTON 1
Rosedale Abbey
LOCKTON EAST 1
NORTHALLERTON
LOCKTON 8
SCARBOROUGH
FELIXKIRK
NORTH YORK MOORS
WYKEHAM 1
Wilton
PICKERING 1
NORTH FORDON G1
FILEY
VALE OF PICKERING
Hunmanby
KIRBY MISPERTON 1
MALTON 3
East Knapton
HUNMANBY 1
NORTH FORDON G3
FORDON 1 (WOLD NEWTON)
FORDON 2
Crayke
MALTON 1
BUTTERWICK
Flamborough
MALTON
NORTH FORDON G2
BRIDLINGTON
BROWN MOOR
Acklam
YORKSHIRE WOLDS
NORTH DALTON 1
YORK
HAYTON WELL NO.1
Market Weighton
SELBY NO.2
COCKLE PITS
KINGSTON UPON HULL
WINESTEAD 1
Patrington
GOOLE
LINE OF SECTION
W
E
SCUNTHORPE
GRIMSBY
Cleethorpes
BRIGG
CLEETHORPES 1
Caistor
NORTH EWSTER
Nettleton
NETTLETON BOTTOM
TETNEY LOCK 1
DONCASTER
SALTFLEETBY 1
GAINSBOROUGH
MARKET RASEN
LINE OF SECTION
LINCOLNSHIRE WOLDS
LINCOLN
Stixwould
HALTON HOLEGATE 1
SKEGNESS
SKEGNESS
47/29A-1
CLAXBY 1
COTMOOR LANE
FULBECK AIRFIELD FB1
LINCOLNSHIRE FENS
RUSKINGTON 1
SIBSEY NO.1
72/78
FISKERTON 1
NEWARK-ON-TRENT
SLEAFORD
BURTON LODGE
72/77b
Ancaster
BOSTON
COPPER HILL
GABLES FARM
HURN CORNER SCREDINGTON
S
CROPWELL BRIDGE
COX'S WALK NO.1
MAREHAM GRANGE
HELPRINGHAM 1
GRANTHAM
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40 km
GREAT OSGROVE WOOD
PETERBOROUGH
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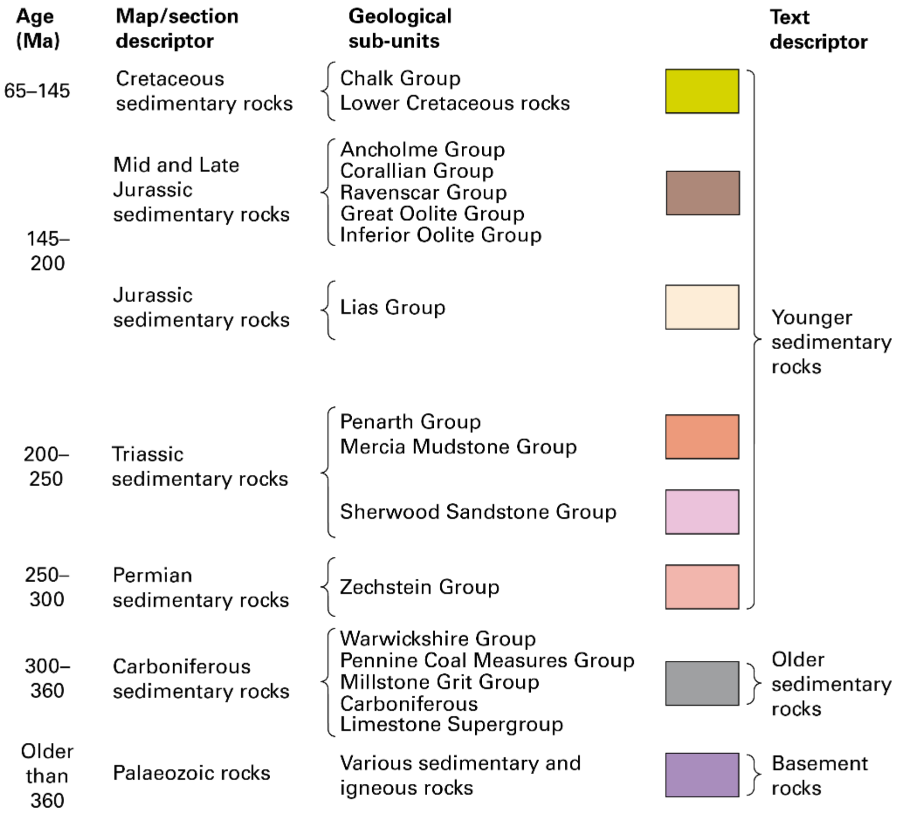

Figure 3 Generalised geological map and key showing the distribution of younger sedimentary rocks, older sedimentary rocks and basement rocks in the onshore Eastern England region. The inset map shows the extent of the region in the UK. See Figures 4 and 5 for schematic cross-sections. The 'Geological 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.

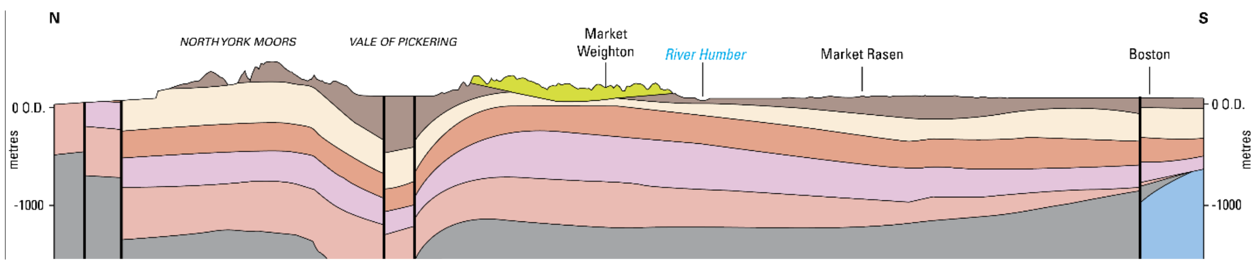

Figure 4 Schematic north-west to south-east cross-section through the Eastern England region. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

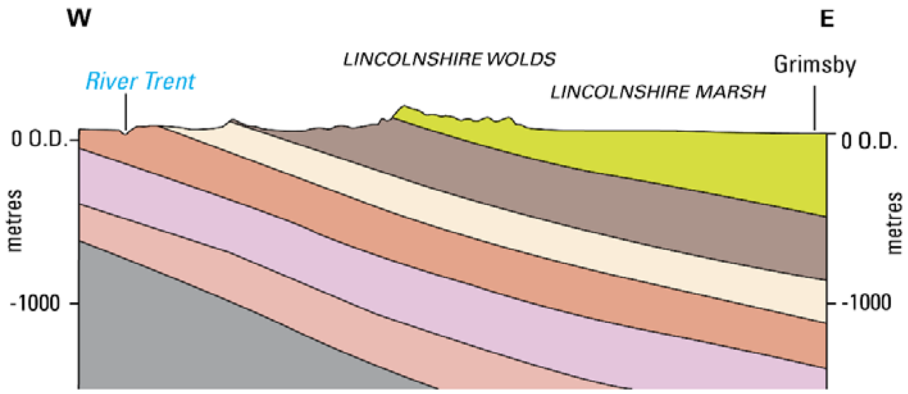

Figure 5 Schematic west–east cross-section through the Eastern England region south of the Humber. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

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 EASTERN ENGLAND REGION

Table 3 presents a generalised vertical section (GVS) for the Eastern 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 Eastern England region, the GVS groups the rocks of the UK into three age ranges: younger sedimentary rocks (Cretaceous, Jurassic, Triassic and Permian), older sedimentary rocks (Carboniferous) and basement rocks (Devonian 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 rock units (LSSR) and evaporites (halite) within the younger and older sedimentary rocks, and higher strength rock (HSR) units in the basement rocks.

The mudstone-dominated basement rocks in the region, comprising Palaeozoic sedimentary rocks of Cambrian, Ordovician, Silurian and Devonian age, lie 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 a HSR PRTI and are not considered further.

The PRTIs are described in Table 3 in stratigraphical order from youngest to oldest (i.e. in downward succession), grouped by the three age ranges: younger sedimentary rocks, older sedimentary rocks and basement rocks. The descriptions include the distribution of the PRTI at surface (outcrop) and where the PRTI is present below the surface (subcrop) within the depth range of interest, along with key evidence for the interpretations. The main geological properties of the PRTIs and how these vary across the region are also summarised. Data are mostly taken from the BGS Regional Guide to Eastern England (Kent, 1980) and other published sources (see references). They may include terminology or nomenclature that has been updated since those publications were released. The term ‘mudstone’ follows BGS usage to include claystone and siltstone-grade siliciclastics (Hallsworth and Knox, 1999). The location of boreholes referred to in this chapter is shown on Figure 3.

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

Maps showing the regional distribution of PRTIs at 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 distribution of all PRTIs is provided in Figure 9.

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Table 3 Schematic GVS for the Eastern 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 Figure 6, Figure 7 and Figure 8 for the regional lateral distribution of PRTI's amalgamated by host rock type (i.e. LSSR, EVAP and HSR respectively).

Geological period		Geological unit	Dominant rock type	Potential rock types of interest			Principal aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS	Jurassic–Cretaceous	Chalk Group	Chalk	N/A	N/A	N/A	Chalk Group
		Early Cretaceous rocks	Mudstone, sandstone and ironstone	N/A	Tealby and Speeton Clay formations	N/A	Hunstanton Formation (Carstone Formation and Spilsby Sandstone Formation of minor importance)
		Ancholme Group undivided (south of region)	Mudstone, siltstone, limestone and sandstone	N/A	Kimmeridge Clay, Ampthill Clay, Oxford Clay and West Walton formations	N/A	Brantingham Member (of the West Walton Formation)
		Corallian Group	Limestone, sandstone and mudstone	N/A	N/A	N/A	Corallian Group
		Ravenscar Group	Sandstone, siltstone and mudstone	N/A	Scalby, Cloughton and Saltwick formations	N/A	N/A
		Great Oolite Group	Sandstone and limestone with mudstone	N/A	N/A	N/A	Blisworth Limestone Formation
		Inferior Oolite Group	Limestone, sandstone, mudstone and ironstone	N/A	N/A	N/A	Lincolnshire Limestone Formation
		Lias Group	Mudstone with sandstone, limestone and ironstone	N/A	Whitby, Redcar, Charmouth and Scunthorpe Mudstone formations	N/A	N/A
	Triassic	Penarth Group (combined with Mercia Mudstone Group in NGS3D)	Mudstone, siltstone and sandstone	N/A	Lilstock and Westbury formations	N/A	N/A
		Mercia Mudstone Group	Mudstone with local siltstone and evaporite deposits of anhydrite, gypsum and halite	N/A	Blue Anchor, Branscombe Mudstone and Sidmouth Mudstone formations	Esk Evaporite Member Röt Halite Member (offshore)	N/A
		Sherwood Sandstone Group	Sandstone with conglomerate and mudstone	N/A	N/A	N/A	Sherwood Sandstone Group
	Permian	Zechstein Group	Dolomitised limestone, dolomite and mudstone with varied evaporites	N/A	N/A	Sneaton Halite, Boulby Halite and Fordon Evaporite formations	Brotherton Formation (Upper Magnesian Limestone), Cadeby Formation (Lower Magnesian Limestone)
		Rotliegendes Group	Sandstone	N/A	N/A	N/A	Rotliegendes Group (below 400 mOD)
OLDER SEDIMENTARY ROCKS	Carboniferous	Warwickshire Group	Sandstone and mudstone	N/A	Etruria Formation	N/A	N/A
		Pennine Coal Measures Group	Mudstone, siltstone, sandstone and coal	N/A	N/A	N/A	N/A
		Millstone Grit Group	Sandstone, siltstone and mudstone	N/A	N/A	N/A	N/A
		Yoredale Group	Mudstone, sandstone, limestone and coal	N/A	N/A	N/A	N/A
		Craven Group	Mudstone, limestone, and sandstone	N/A	N/A	N/A	N/A
		Carboniferous Limestone Supergroup	Limestone	N/A	N/A	N/A	Carboniferous Limestone Supergroup (below 400 mOD)
BASEMENT ROCKS	Early Palaeozoic	Ordovician igneous rocks (lavas)	Andesite and dacite lavas	Extrusive igneous rocks	N/A	N/A	N/A
		Intrusive igneous rocks (Wash batholith)	Granite (inferred from geophysics only)	Intrusive igneous rocks	N/A	N/A	N/A
		Early Palaeozoic rocks	Mudstone, siltstone and sandstone, variably metamorphosed, with various igneous rocks	N/A	N/A	N/A	N/A

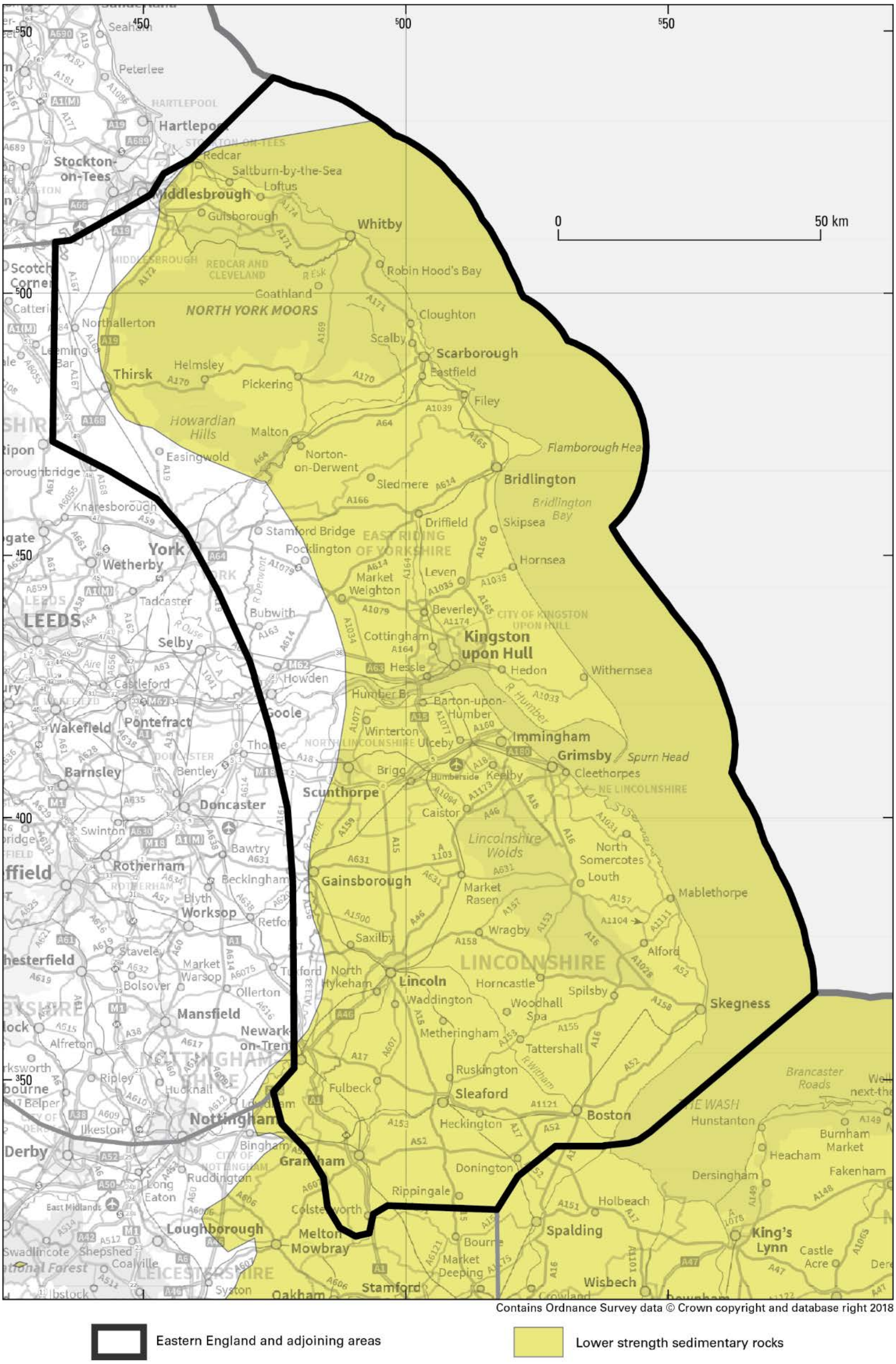

Figure 6 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Eastern England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI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

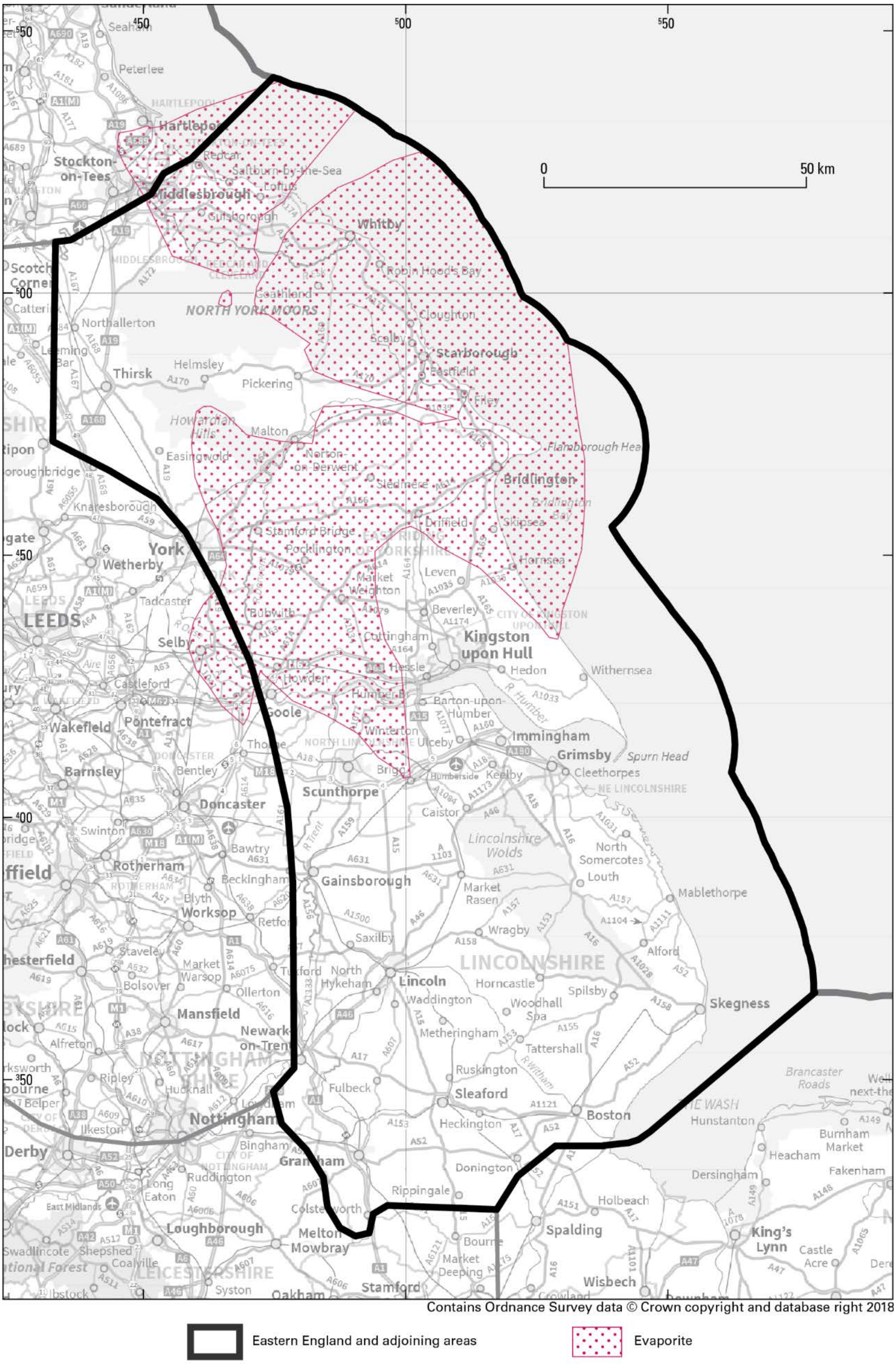

Figure 7 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the Eastern England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI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

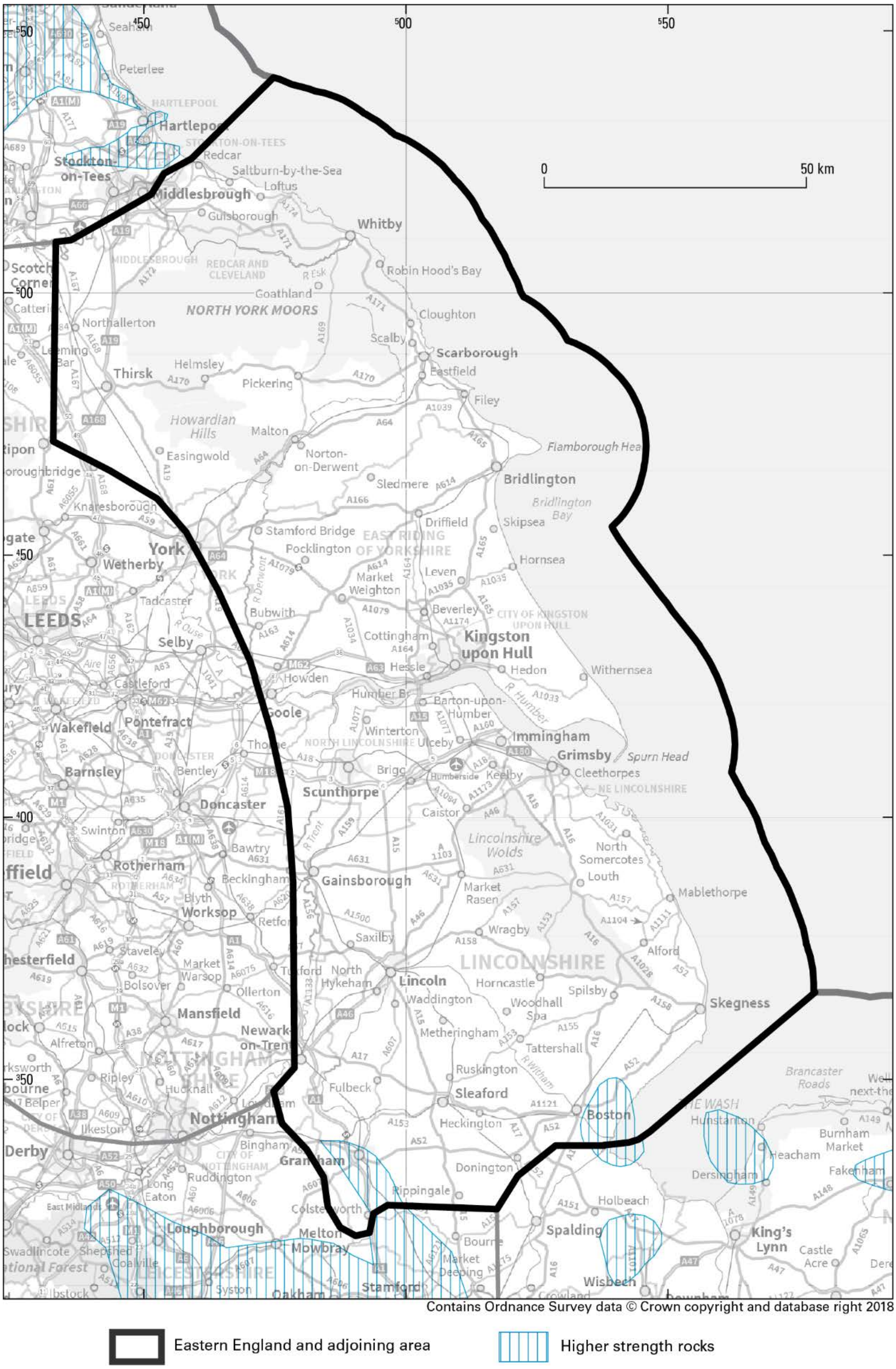

Figure 8 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Eastern England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI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

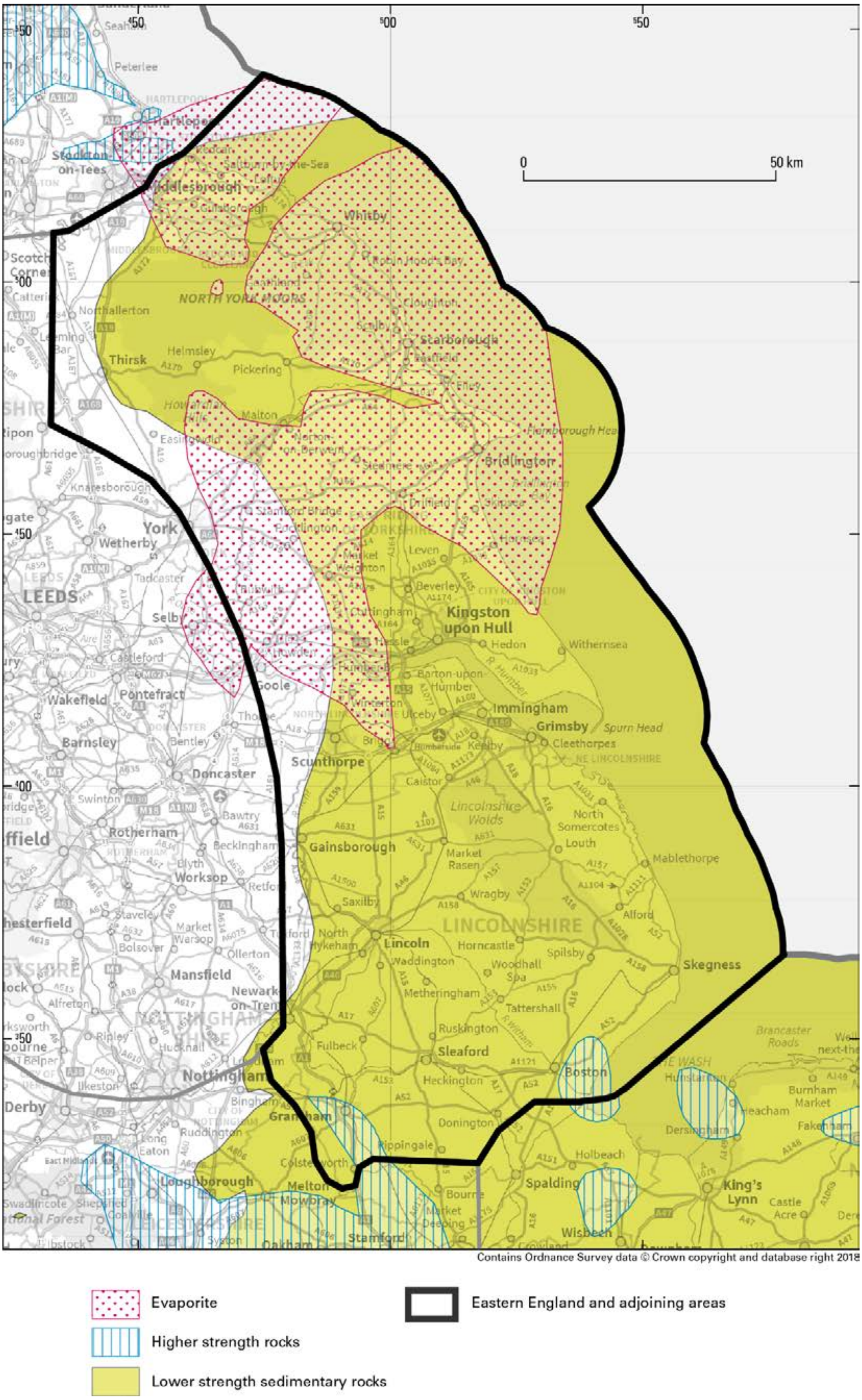

Figure 9 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Eastern England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey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

4.2.1 Younger sedimentary rocks

4.2.1.1 EARLY CRETACEOUS ROCKS (INCORPORATING THE SPEETON CLAY FORMATION AND TEALBY FORMATION PRTIS) – LSSR

These Early Cretaceous formations consist predominantly of siliceous and calcareous mudstone lithologies with interbedded units of clays and mudstones, specifically the Speeton Clay Formation and the Tealby Formation. They are present at outcrop and in the subsurface over relatively small areas of the region within the top part of the 200 to 1000 m depth range of interest (Figure 11). The Tealby Formation (Kent, 1980; Rawson, 2006) mudstones comprise part of the varied Early Cretaceous succession that consists mostly of sandstone and ironstone; the formation is present only in the Lincolnshire Wolds, from The Wash northwards to near Caistor (Figure 3). In contrast, the Speeton Clay Formation, which spans a greater age range of the Early Cretaceous, is thicker, but is present only in the area between East Knapton to Filey Bay (north Yorkshire Wolds) and offshore from there (Figure 10); exploration boreholes and seismic profiles prove that it is present in the subsurface beneath the Chalk Group in the north Yorkshire Wolds as far south as an east–west line drawn approximately through Bridlington (Neale, 1974; Kirby and Swallow, 1987; Rawson, 2006; Hopson et al., 2008).

Principal information sources

The Speeton Clay Formation is poorly known at surface because it crops out only intermittently as a narrow band across the northern escarpment of the north Yorkshire Wolds from East Knapton eastwards to Filey Bay (Figure 11). Furthermore, the outcrop is commonly covered by superficial deposits or is landslipped (BGS, 1998b). Consequently, the surface outcrop information has been derived mostly from the natural exposures in Filey Bay (Neale, 1974; Rawson, 2006), although the rocks are only intermittently exposed. The distribution and thickness of the formation in the subsurface within the depth range of interest is known from a number of hydrocarbon exploration boreholes (e.g. Fordon No. 2) and from geophysical seismic profiles below the Chalk Group of the north Yorkshire Wolds and offshore from the Filey–Bridlington area (Kirby and Swallow, 1987). Cores and geophysical wireline logs provide information on the lithology of the formation.

The Tealby Formation crops out in a narrow, poorly exposed band from The Wash northwards to near Caistor. The beds dip at 1 to 2º to the east below the Lincolnshire Wolds escarpment and are present just within the top of the depth range of interest offshore from the Lincolnshire coast (e.g. Borehole 47/29A-1). Information on the lithology and thickness has been derived mostly from surface exposures and sparse boreholes below the Lincolnshire Wolds and The Wash.

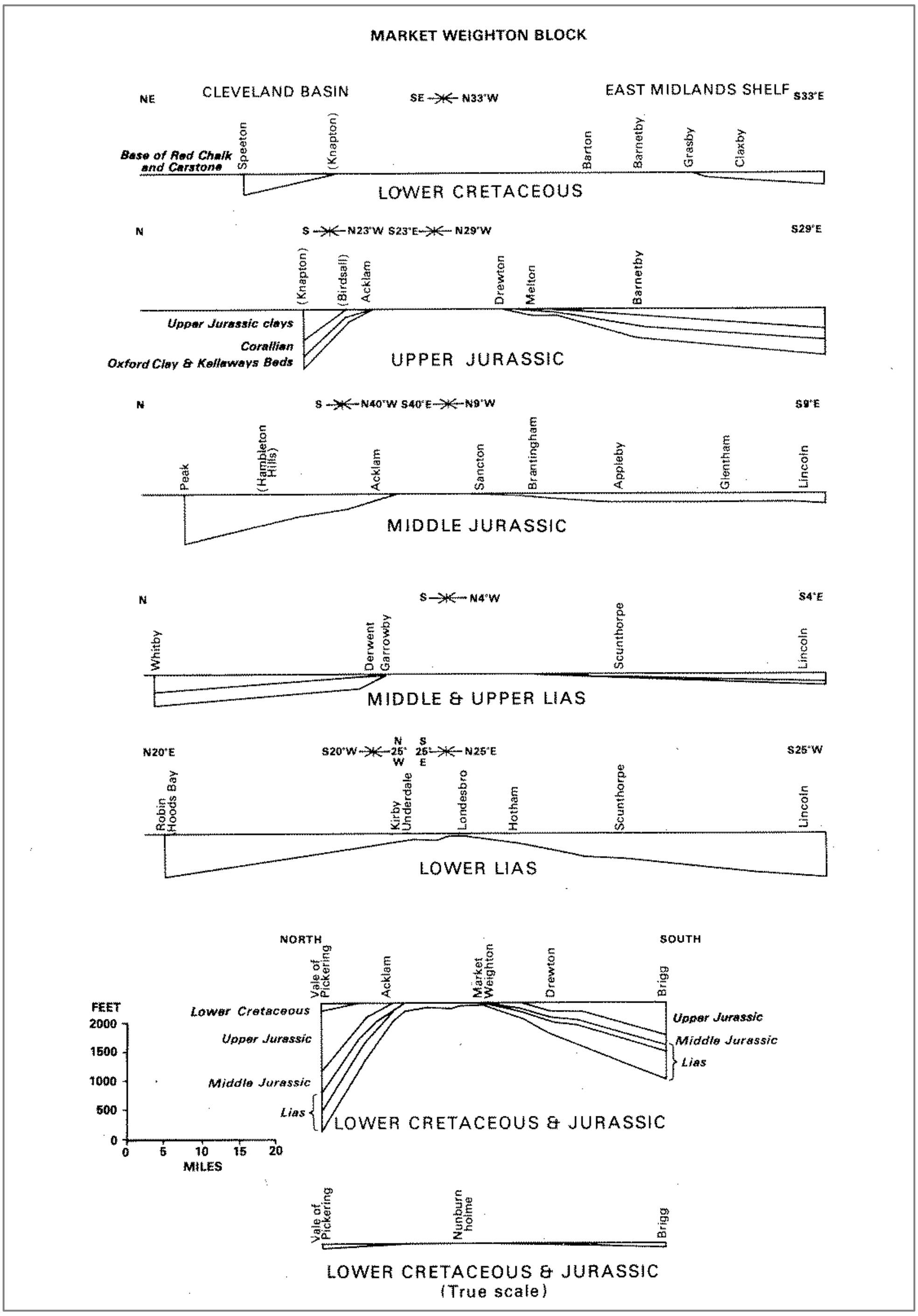

Figure 10 Diagrammatic sections across the Market Weighton high during the Jurassic and Early Cretaceous, from Kent (1980). Note the thinning from the north and south towards the Market Weighton high (block), and the absence, due to Cretaceous erosion, of all but the lower Lias Group rocks over this structure. The lower two sections illustrate the full Cretaceous–Jurassic succession from the Vale of Pickering southward to the Brigg area. British Geological Survey © UKRI 2018.

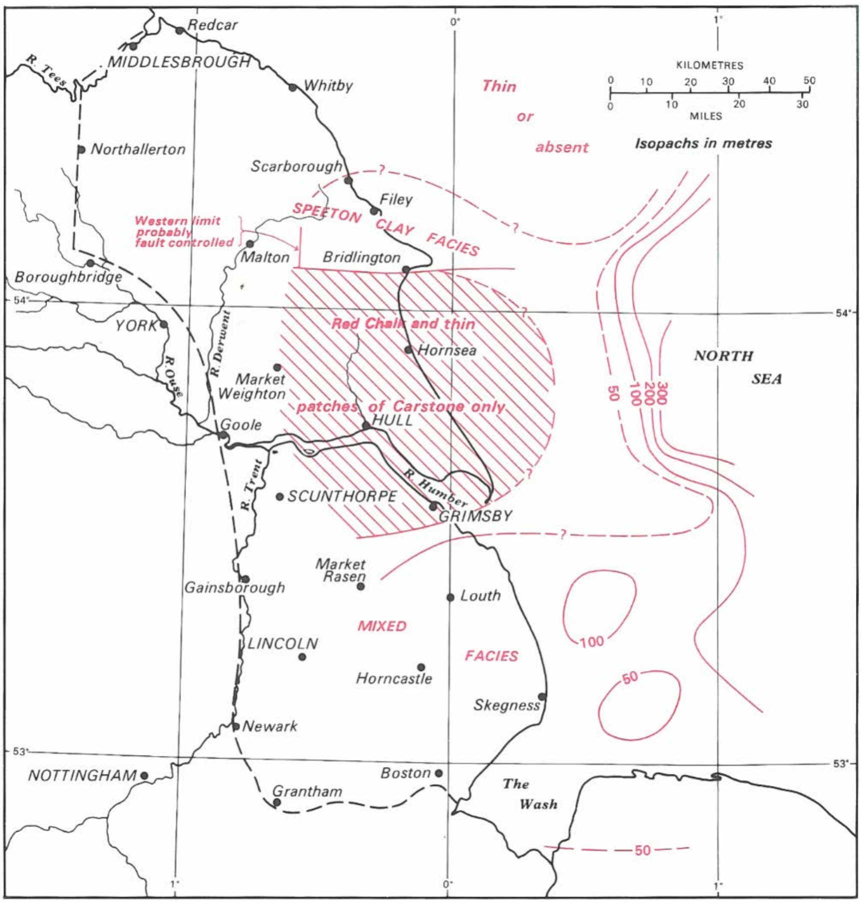

Figure 11 Thickness variations in the Early Cretaceous rocks. Note the limited extent of the Speeton Clay Formation (shown here as Speeton Clay Facies) to the north of Bridlington. The Tealby Formation forms part of the 'mixed facies' present in the south of the region. Both formations are absent over the cross-hatched area between Bridlington and Grimsby. From Kent (1980). British Geological Survey © UKRI 2018.

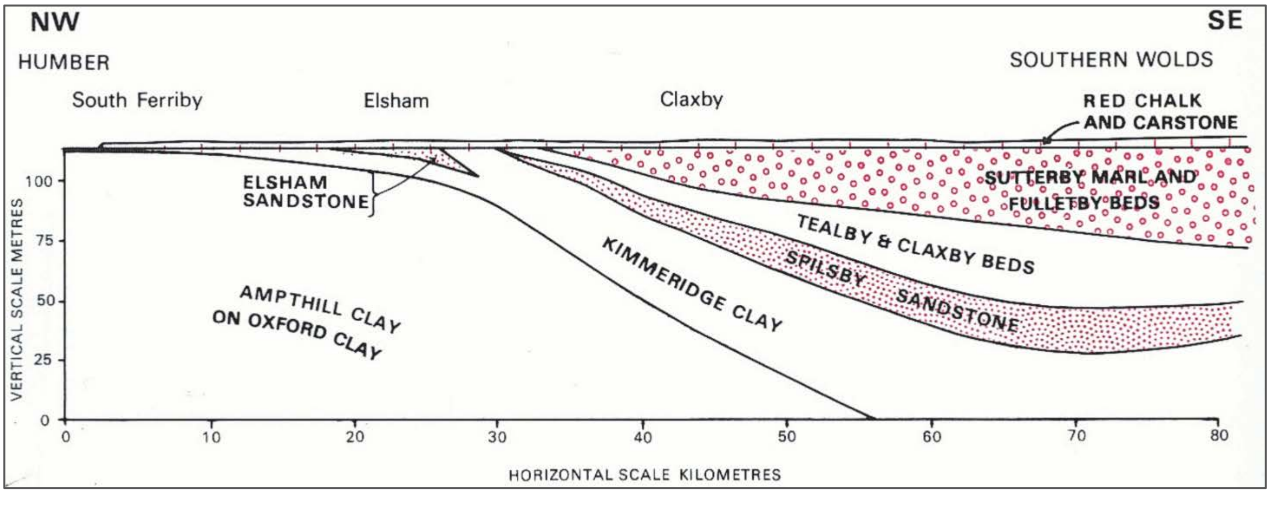

Figure 12 Generalised section of the Late Jurassic rocks and the Early Cretaceous rocks across Lincolnshire. Note the thinning and wedging out of the Tealby Formation (and Claxby Ironstone Formation) towards the north-west, and the presence of the laterally impersistent Elsham Sandstone Member within the Kimmeridge Clay Formation, which also thins towards the north-west. From Kent (1980). British Geological Survey © UKRI 2018.

Rock type descriptions

The Speeton Clay Formation ranges in thickness from 102 m at outcrop in Filey Bay to between 129 m and 212 m as proved in exploration boreholes west of Hunmanby (North Fordon G1; North Fordon G2; North Fordon G3, and Hunmanby No. 1) (Neale, 1974; Hopson et al., 2008). In the small onshore basin, north of an east–west line taken approximately through Bridlington (Figure 11), seismic profiles indicate that the formation reaches up to 300 m, or possibly 500 m, thick west of Hunmanby, within the depth range of interest below the Chalk Group of the north Yorkshire Wolds (Kirby and Swallow, 1987; Rawson, 2006). It thins rapidly southwards over a distance of 15 km towards the Market Weighton high (BGS, 1998b) but is not present west of East Knapton (Figure 11) where the Hunstanton Formation (formerly Red Chalk) rests unconformably on the Kimmeridge Clay Formation (Neale, 1974; BGS, 1998b). Offshore, the BGS Borehole 81/43, located about 60 km north-east of Filey Bay, proved 90 m of calcareous and non-calcareous mudstone. The lithology, as proved from outcrop and in cores of boreholes as noted, consists predominantly of siliceous mudstone and claystone, calcareous mudstone (‘cementstone beds’) and phosphatic nodules, along with glauconitic mudstone and nodules (Rawson, 2006). The uppermost beds pass gradationally up to the overlying Hunstanton Formation. The Speeton Clay Formation is underlain by mudstones of the Kimmeridge Clay Formation (Ancholme Group), which also represents a PRTI.

The Tealby Formation, present only in Lincolnshire, is subdivided into three members, in downward sequence: the Upper Tealby Clay (up to 14 m thick); the Tealby Limestone (0 to 5 m thick), and the Lower Tealby Clay (13 m thick) (Rawson, 2006). To the south of Skegness, the middle limestone unit pinches out and is not present farther south. In The Wash area, up to 22.6 m of siliceous mudstone, calcareous mudstone and shelly mudstone were proved in BGS boreholes 72/77b and 72/78 (Wingfield et al., 1978) above the depth range of interest; onshore the unit is 28 m thick in the BGS Skegness Borehole (Wingfield et al., 1978) but, again, this lies above the depth range of interest. The unit thins northwards towards the Humber (Figure 12): 17 m were proved south of Grimsby in the Tetney Lock No. 1 Borehole and 9 m in the Cleethorpes No. 1 Borehole (Berridge and Pattison, 1994; Cameron et al., 1992). In the Nettleton area, north Lincolnshire, the formation (up to 13 m thick) was formerly exposed during quarrying for the underlying Claxby Ironstone Formation (Berridge and Pattison, 1994), but the mudstones contain ferruginous ooids in this area. In Lincolnshire, the formation dips gently to the east: the Skegness Borehole and boreholes in The Wash indicate that the subsurface extent of the Tealby Formation, within the depth range of interest, is present only about 20 km offshore from the Lincolnshire Coast (Borehole 47/29A-1). In mid Lincolnshire, the Upper Tealby Clay is 5.49 m thick and the lower unit 11 m thick, the base of the latter proven at 166 m depth in the Saltfleetby 1 Borehole, i.e. above the depth range of interest.

4.2.1.2 ANCHOLME GROUP (INCORPORATING THE KIMMERIDGE CLAY, AMPTHILL CLAY, OXFORD CLAY AND WEST WALTON FORMATIONS PRTIS) — LSSR

This rock unit consists predominantly of mudstone (claystone and siltstone) and represents a PRTI that crops out, and underlies the east of the region within the depth range of interest, between The Wash northwards to Market Weighton (Figure 13). The Ancholme Group is up to 350 m thick in mid Lincolnshire (e.g. 322 m in the Halton Holegate 1 Borehole; 370 m in the Saltfleetby 1 Borehole) and 295 m thick in the Vale of Pickering (Kent, 1980). However, there are marked changes in the overall thickness and lithology of the group across the region, notably the pronounced thinning from mid Lincolnshire northwards to the Market Weighton high (Figures 4 and 13). The group thickens again northwards into the Vale of Pickering (295 m) but is much thinner (about 35 m) in the North York Moors (Cleveland basin) associated with a lateral passage from mudstone to calcareous sandstone and limestone (Corallian Group) (Figure 14). The component rock formations making up the Ancholme Group also vary greatly in thickness across the region.

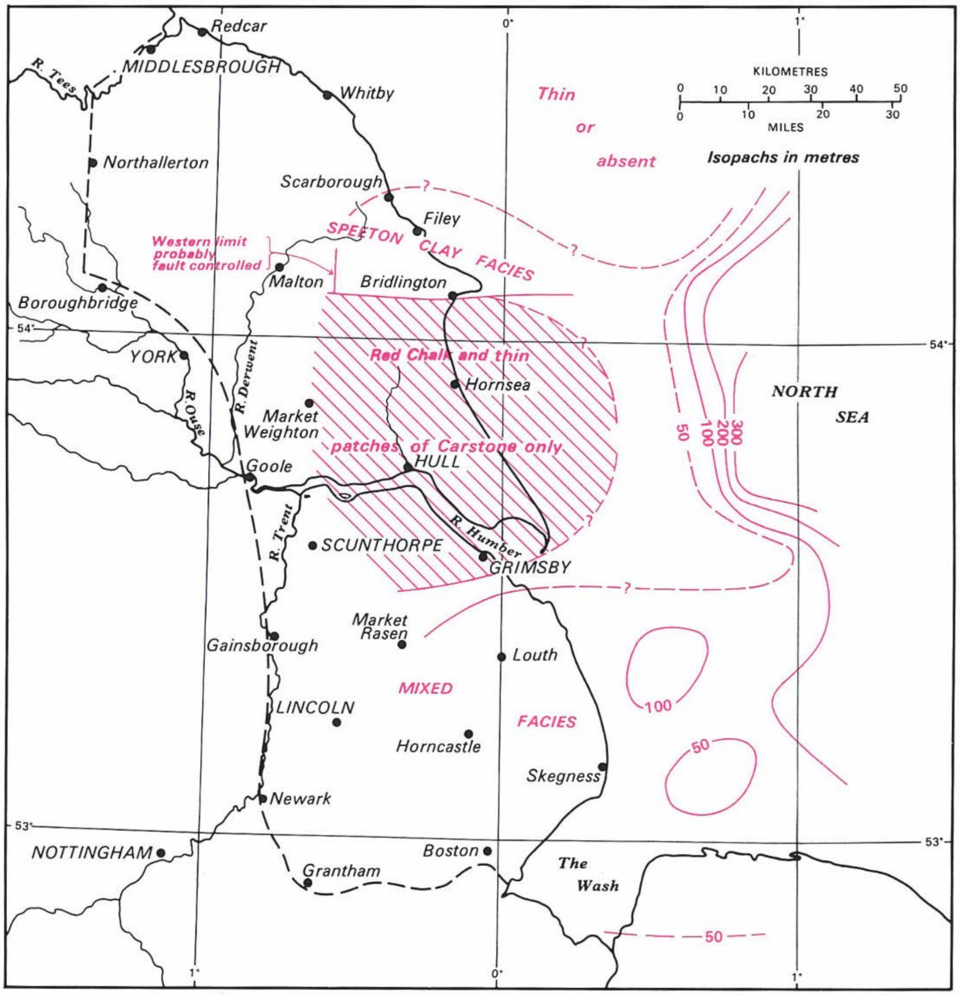

Figure 13 Thickness variations in the Late Jurassic rocks (Ancholme Group). From Kent (1980). British Geological Survey © UKRI 2018.

Principal information sources

The surface outcrop of the Ancholme Group is poorly known because the rocks generally underlie low-lying farmland, much of it covered by thin superficial deposits. However, the lower mudstones have been widely exploited for brick clay in the adjacent area around Peterborough (south-west of the region), which, together with boreholes drilled for hydrocarbons, groundwater and minerals, provide sufficient detail to characterise the lithology and thickness of the rocks. In north-east Yorkshire (Cleveland basin) the mudstone is generally thinner, but is well exposed in places along the Yorkshire coast (e.g. the Scarborough area). It has also been proved offshore in the North Sea (Figure 7) in a number of exploration boreholes.

In the subsurface, the rocks dip gently (1 to 3º) to the east or east-north-east and are overlain by Cretaceous rocks, including the Chalk Group, in the Lincolnshire Wolds from The Wash northwards to the Filey area. In the Filey to the Vale of Pickering area, the Ancholme Group is overlain by another PRTI, the Speeton Clay Formation. In the Vale of Pickering, the rock unit is well known from seismic surveys and hydrocarbon exploration boreholes (e.g. Fordon No. 1; Kirby Misperton No. 1 and Hunmanby No. 1). Information on the lithology is based mostly on cores and geophysical wireline logs. Farther south, in the Lincolnshire Wolds, the group was cored in the BGS Nettleton Bottom Borehole (Gaunt et al., 1992).

Rock type descriptions

In the area from The Wash northwards to Hull, the Ancholme Group is subdivided into five formations based on their lithology. In downward succession these are: the Kimmeridge Clay Formation; the Ampthill Clay Formation; the West Walton Formation; the Oxford Clay Formation and the Kellaways Formation. The Kellaways Formation (up to 8 m thick) consists of thin siliceous mudstone overlain by siltstone and sandstone; it is, therefore, not a PRTI. The four overlying mudstone-dominated formations are PRTIs, although the relatively thin (about 15 m) West Walton Formation has a high calcareous content.

The Kimmeridge Clay Formation is overlain unconformably by Cretaceous rocks comprising the Spilsby Sandstone Formation or the Carstone Formation (a calcareous sandstone) in Lincolnshire (Figures 5 and 12), and by the Speeton Clay Formation (a PRTI) below the north Yorkshire Wolds and offshore from Filey Bay. It overlies the Ampthill Clay Formation (another PRTI). The Kimmeridge Clay Formation is poorly known from surface exposures in the region as it is generally either poorly exposed or overlain by superficial deposits or Cretaceous rocks. However, the distribution, lithology and thickness of the formation are well known from a number of hydrocarbon exploration boreholes, as well as small brick pits. The beds dip at about 1 to 2º to the east and are present within the depth range of interest over a broad tract in the east of the region from The Wash to the Grimsby area with a maximum thickness of 130 m and 135 m respectively (Kent, 1980; Berridge and Pattison, 1994). The base of the formation lies at 375 m depth in the Saltfleetby 1 Borehole. The formation maintains this thickness into mid Lincolnshire but, like other formations of the Ancholme Group, it thins northwards towards the Market Weighton high (e.g. 12 m near Patrington; Winestead No. 1 Borehole) and is progressively cut out (overstepped) by Cretaceous rocks north of Caistor, disappearing at the Humber (Figures 12 and 13). In north Lincolnshire, east of Brigg, a medium- to coarse-grained calcareous sandstone unit, the Elsham Sandstone Member, (about 10 m thick) forms a laterally impersistent lens in the lower part of the formation (Figure 12). The lateral extent of this unit is poorly known (Gaunt et al., 1992), but it wedges out at outcrop (Figure 12) and is unlikely to be present within the depth range of interest. The Kimmeridge Clay Formation is also present to the north of the Market Weighton high, in the Vale of Pickering, where the Fordon No. 1 Borehole proved 250 m of organic-rich mudstone, while at the coast, near Filey, it is 300 m thick (Hunmanby No. 1 Borehole). Over much of the Vale of Pickering the Kimmeridge Clay Formation lies above the depth range of interest, but east of Hunmanby it is present within the depth range underlying the Speeton Clay Formation (a PRTI). The formation consists of alternating soft and shelly siliceous mudstone, shelly mudstone, calcareous mudstone, thin argillaceous limestone and organic-rich mudstone (oil shale). It differs from the underlying Ampthill Clay Formation in its general absence of pyrite. Uplift and erosion of the North York Moors (Cleveland basin) during Tertiary times removed the Kimmeridge Clay Formation from the moorland area.

The Ampthill Clay Formation is similar lithologically to the underlying Oxford Clay Formation, consisting of grey siliceous mudstone, calcareous in part, with sparse, thin limestone beds. It is present within the depth range of interest in the east of the region from the Lincolnshire Fens to the Humber. The formation ranges in thickness from 65 m near Stixwould, thickening northwards to about 90 m in boreholes in the Humber and Grimsby areas (Kent, 1980; Gaunt et al, 1980; Berridge and Pattison, 1994) and 122 m in the Saltfleetby 1 Borehole. However, it thins northwards from Brigg towards the Market Weighton high, and is absent over this area below the overlying Cretaceous rocks (Figures 4 and 10). The formation is present again, at depth, to the north of the Market Weighton high (e.g. 25 m thick in the BGS Brown Moor Borehole; Gaunt et al., 1980). However, boreholes located farther north in the Vale of Pickering indicate that the formation thins northwards around Malton and is absent in north-east Yorkshire (Cleveland basin) due to the lateral passage to calcareous sandstone and limestone (Corallian Group) (Figure 14).

The West Walton Formation is only present in the subsurface in the Lincolnshire Fens where it is 10 to 15 m thick, but it is 21 m thick in the Saltfleetby 1 Borehole and up to 24 m were proved in boreholes in the Grimsby area (Berridge and Pattison, 1994). The formation is distinguished by its harder lithology consisting of dark grey, siliceous mudstone, calcareous mudstone, siltstone and, locally, with beds and concretions of fine-grained limestone. In a similar manner to the overlying unit, it passes laterally northwards in the Cleveland basin to calcareous sandstone and limestone (Corallian Group).

The Oxford Clay Formation is up to 80 m thick in central Lincolnshire within the depth range of interest, thinning northwards to 50 m near Brigg and 33 m in the Grimsby area (30 m thick in the Saltfleetby 1 Borehole). To the north it thins more markedly and is absent across the Market Weighton high (Gaunt et al., 1980; Berridge and Pattison, 1994). North of Market Weighton the formation is present again at Garrowby, and reaches 35 m thick on the Yorkshire coast. The formation comprises three subdivisions: the upper unit (Weymouth Member; about 30 m thick) consists of pale grey siliceous and calcareous mudstone interbedded with darker grey calcareous mudstone. In the Vale of Pickering and north-east Yorkshire the two lower mudstone units pass laterally to calcareous sandstone and limestone (Osgodby Formation) so that on the Yorkshire Coast the Oxford Clay Formation is represented by only 35 m of the upper unit (Weymouth Member). The middle unit (Stewartby Member; about 26 m thick) is a pale grey, silty, calcareous mudstone.

The lower unit (Peterborough Member; about 16 m thick) is a grey-brown, organic-rich siliceous mudstone with shell beds, and was exploited for brickmaking in the Peterborough area (to the south-west of the region).

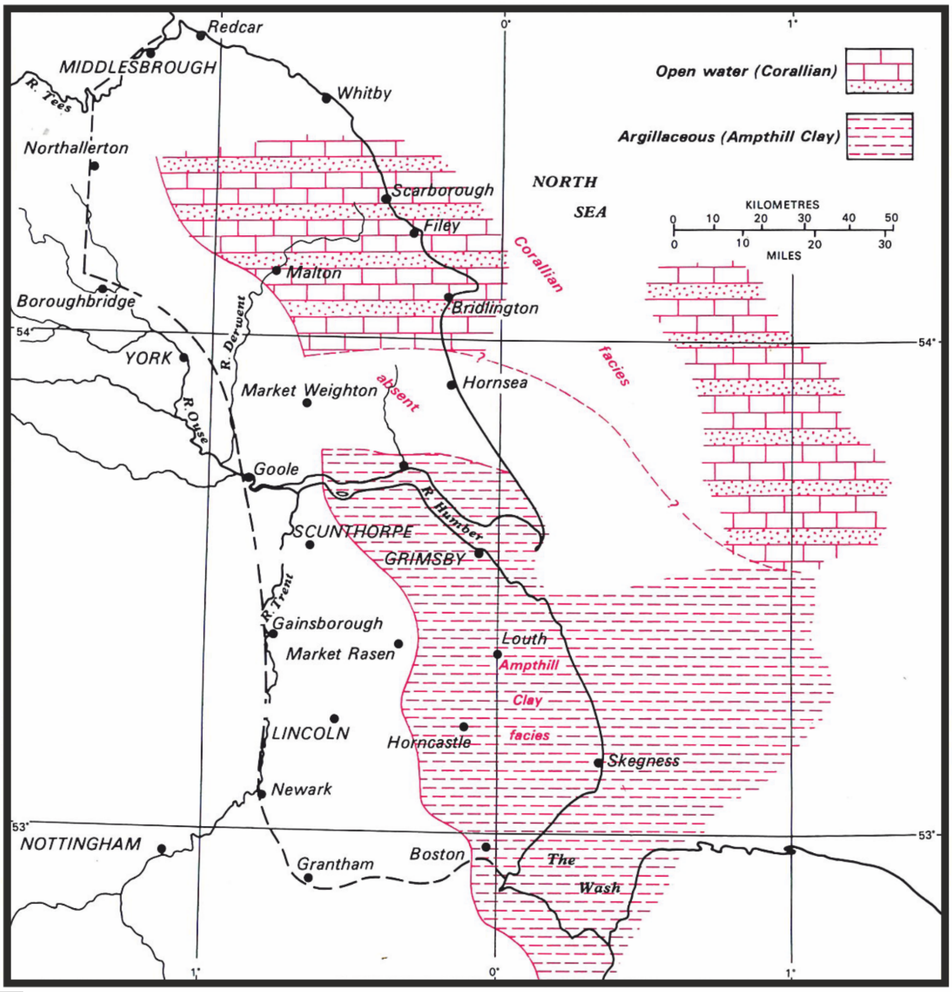

Figure 14 Geographical variations in the rock types during the middle part of the Oxfordian (Ampthill Clay Formation and Corallian Group). Note the calcareous sandstone and limestone lithology (Corallian Group) in the Cleveland basin, and the contrasting mudstone (Ampthill Clay Formation) lithology in the East Midlands shelf, south of the Market Weighton high. From Kent (1980). British Geological Survey © UKRI 2018.

4.2.1.3 Ravenscar Group (incorporating the Scalby, Cloughton and Saltwick formations PRTIs) — LSSR

This rock unit consists of variable proportions of mudstone, sandstone and limestone, and is restricted in its distribution to the Cleveland basin (north-east Yorkshire) (Hemingway, 1974; Powell, 2010; Barron et al., 2012) (Figure 3). The mudstones represent a PRTI that underlie much of north-east Yorkshire but, within the depth range of interest, the rocks are generally restricted to downfaulted areas such as the Vale of Pickering (Figure 3) where the base of the group lies at about 300 to 500 m depth. The unit thins markedly southwards towards the Market Weighton high. To the south of this structure, in Lincolnshire and the East Midlands, the Ravenscar Group is not distinguished due to lateral changes in rock type.

The Ravenscar Group is absent over the Market Weighton high; it thickens northwards from about 57 m in the Fordon No. 1 Borehole (below the north Yorkshire Wolds) to 200 m in the Whitby area (Kent, 1980; Hemingway, 1974; BGS, 1998a; Powell, 2010) (Figure 15). The rock formations making up the group vary in lithology and thickness across the region. The group is overlain by limestone and calcareous sandstone of the Cornbrash Formation and Osgodby Formation respectively, and is underlain by the thin Dogger Formation (ferruginous sandstone) and, in turn, by the Lias Group mudstones.

Principal information sources

The Ravenscar Group rocks are well known from surface exposures (including quarries) in the North York Moors, especially the coastal cliffs, and in the Howardian Hills located to the south. It was also proved in a number of deep exploration boreholes for groundwater and hydrocarbons in the Vale of Pickering (e.g. Kirby Misperton No. 1 and Cloughton 1) and the north Yorkshire Wolds. Information on the lithology comes from surface exposures and, in boreholes, from core, cuttings and distinctive geophysical log signatures.

Rock type descriptions

With the exception of the downfaulted area of the Vale of Pickering, the Ravenscar Group in the Cleveland basin lies above the depth range of interest. In the Cleveland basin (north-east Yorkshire) five formations are recognised, but only three of these are PRTIs. However, the mudstone:sandstone ratio in these rock units is unpredictable. For instance, the rocks vary markedly both vertically and horizontally, with sandstone and siltstone dominant in some areas, whilst in adjacent areas thick units of mudstone may be present (Powell, 2010). Consequently, it is difficult to generalise the lithology across the region, especially in the down-faulted Vale of Pickering where information on the lithology is based on borehole cuttings and geophysical wireline logs such as Kirby Misperton 1, which proved 160 m of interbedded claystone and sandstone with thin limestones. The uppermost Scalby Formation has the highest proportion of mudstone beds (Hemingway, 1974; Powell, 2010). However, the component formations have not been separately identified within the Ravenscar Group in the Vale of Pickering boreholes within the depth range of interest.

The formations are described in downward succession.

The uppermost unit, the Scalby Formation, includes a thick bed (up to 12 m) of sandstone at the base termed the Moor Grit, which, unlike the sandstones in the underlying formations, can be traced laterally throughout most of the Cleveland basin. The overlying mudstone-dominated Long Nab Member ranges from 23 to 33 m thick, thinning southwards to 5 to 10 m in the Howardian Hills, and is absent over the Market Weighton high. It consists of pale grey, siliceous mudstone with thin, yellow sandstone beds, locally in channels, together with thin coals and seatearth mudstone. The sandstone beds are thinner, and the ratio of sandstone to mudstone is lower in this unit compared to the underlying Saltwick and Cloughton formations.

The Cloughton Formation (up to 85 m thick) includes rock units (members) similar in lithology to the Scalby Formation. It consists predominantly of grey siliceous mudstone with thick, channel-fill lenses and beds of sandstone; the sandstone beds may be locally up to 15 m thick, and may make up to 50 per cent of the formation (Powell, 2010). Thin beds of coal, seatearth mudstone and siderite ironstone nodules may be present. The lateral and vertical distribution of the channel-fill sandstone is generally unpredictable over distances of a few kilometres. In the southern part of the Cleveland basin, beds of limestone and calcareous mudstone (Lebberston Member; about 11 m thick) separate the formation into a lower Sycarham Member (about 38 m thick) and an upper Gristhorpe Member (about 23 m thick). The Lebberston Member pinches out in the northern North York Moors so that in the Whitby to Northallerton area there is a continuous succession of siliceous mudstone and sandstone.

The Saltwick Formation overlies the thin Dogger Formation (ferruginous sandstone) and ranges in thickness from about 50 m on the north Yorkshire coast to 25 m in the Hambleton Hills (Powell et al., 1992; Frost, 1998), thinning southwards to about 10 m in the Howardian Hills, and is absent over the Market Weighton high. The lithology is very similar to the overlying Cloughton Formation, although limestone beds are absent. Again, the lateral and vertical distribution of the channel-fill sandstones is generally unpredictable over distances of a few kilometres.

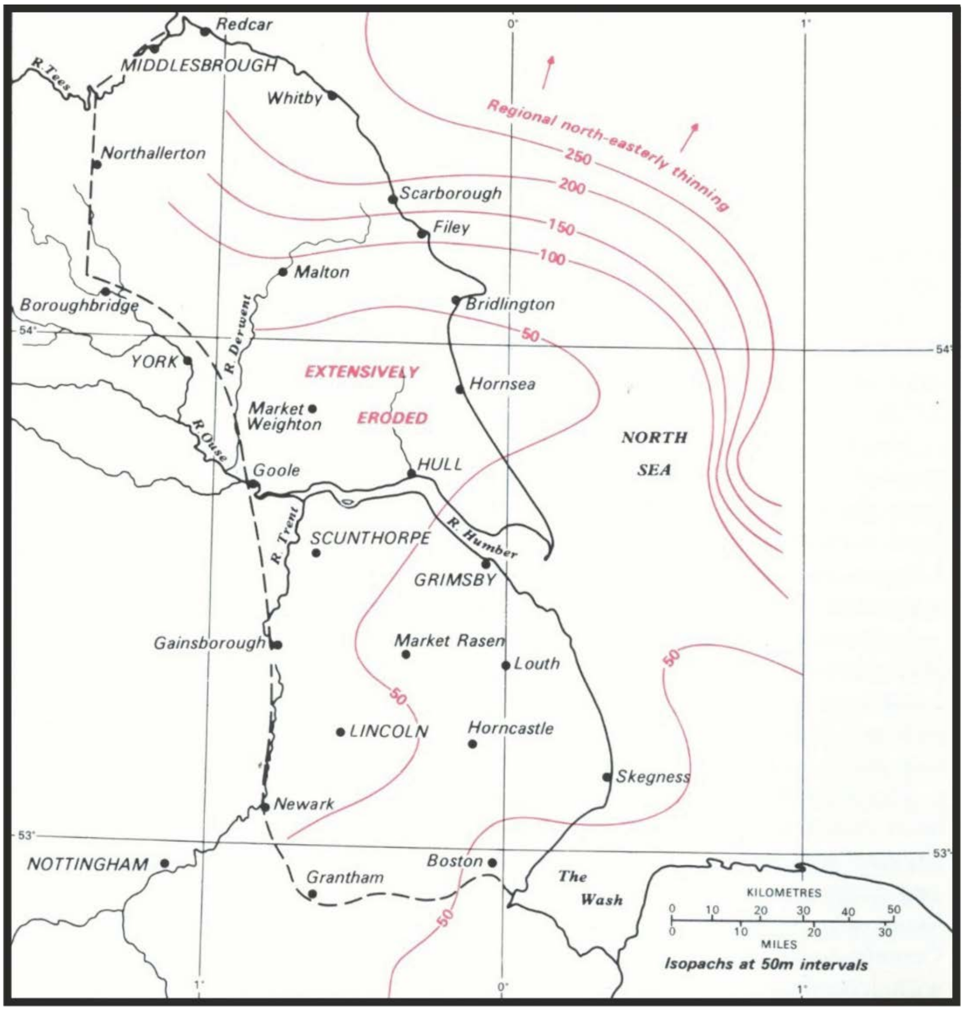

Figure 15 Thickness variations in the Mid Jurassic rocks. From Kent (1980). British Geological Survey © UKRI 2018.

4.2.1.4 LIAS GROUP (INCORPORATING THE WHITBY MUDSTONE, REDCAR MUDSTONE, CHARMOUTH MUDSTONE AND SCUNTHORPE MUDSTONE FORMATIONS PRTIS) — LSSR

The Early Jurassic Lias Group consists predominantly of mudstone and is a PRTI that underlies much of the region within the depth range of interest, especially in north-east Yorkshire (Cleveland basin) where the beds are gently folded, and below the north Yorkshire and Lincolnshire Wolds (Figures 3, 4, 5 and 15). The unit is underlain by the thin Penarth Group and the Mercia Mudstone Group that together comprise a PRTI. At surface, the Lias Group is well exposed on the Yorkshire coast in deeply incised valleys (e.g. Rosedale) and around the margins of the North York Moors (Hemingway, 1974; Cox et al., 1999; Powell, 2010). It thins markedly to the south over the Market Weighton high (Figures 3, 4, 5 and 15), but is thicker and forms a broad, low-lying outcrop in Lincolnshire where it is gently tilted to the east or south-east at about 1º (Kent, 1980).

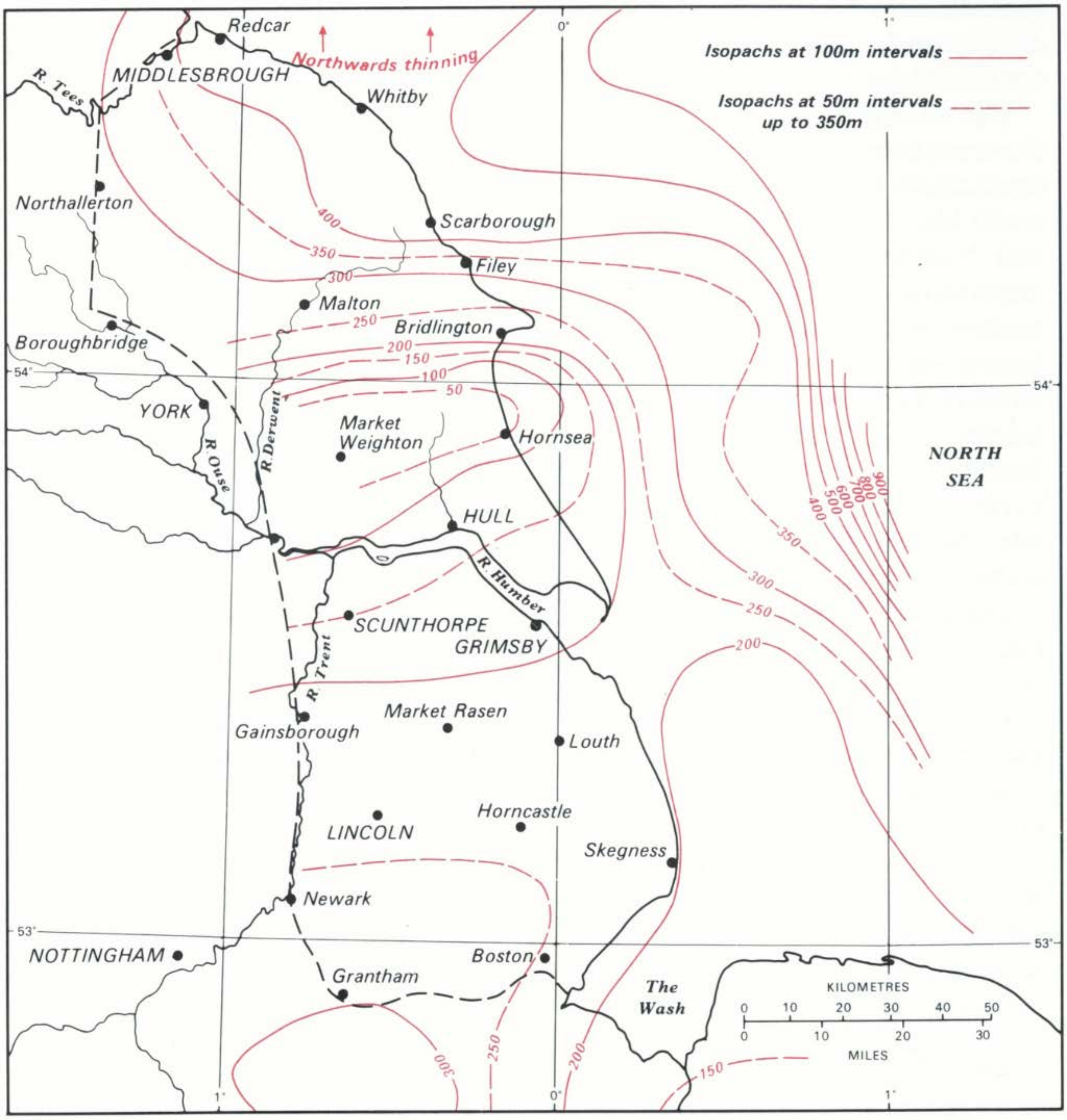

Figure 16 Thickness variations in the Early Jurassic rocks. From Kent (1980). British Geological Survey © UKRI 2018.

Principal information sources

In addition to surface exposures, including former workings for alum, jet, ironstone and brick clay, the lithology and variations in thickness of the Lias Group, at depth, are known from a number of hydrocarbon exploration boreholes and geophysical seismic profiles in the North York Moors (e.g. Lockton East No. 1; Lockton No. 8; Cloughton No. 1; Egton High Moor No. 1; Scaling No. 1; Wykeham No. 1), in the Vale of Pickering (e.g. Pickering No. 1; Kirby Misperton No. 1; Malton No. 1 and No. 3), and in the north Yorkshire Wolds (e.g. Fordon No. 1). Information on the lithology is derived from surface exposures, borehole cuttings, cores and geophysical wireline logs. The thinner succession in the Market Weighton area, and south of here to the Humber, is proven in a number of BGS boreholes in the Humber–Acklam area (Gaunt et al., 1980). In Lincolnshire and the East Midlands, the outcrop is commonly obscured by thin superficial deposits, but below this area the lithology and thickness are known from a number of cored boreholes, including the BGS Nettleton Bottom Borehole (Lincolnshire Wolds) (Gaunt et al., 1992), Halton Holegate 1 Borehole, Saltfleetby 1 Borehole and, farther south near Grantham, the Fulbeck Airfield FB1 and Copper Hill boreholes, and the Helpringham No. 1 Borehole (Berridge and Pattison, 1994).

Rock type description

The Lias Group ranges in thickness across the region (Figure 10) from 250 m near The Wash to 250 to 300 m in mid Lincolnshire, and thins northwards from here to the Market Weighton area (about 40 m) (Kent, 1980; Powell, 2010). The group thickens again northwards to the North York Moors (Cleveland basin) where it is on average about 350 m thick, but reaches 450 m in the Scaling No. 1 Borehole. It is present within the depth range of interest beneath much of north Yorkshire (Cleveland basin), except for the northern part of the North York Moors, and the Vale of Pickering. The group thins markedly to the south of the Vale of Pickering beneath the north Yorkshire Wolds and is not present within the depth range of interest over the Market Weighton high (Figures 4 and 10). South of this area the group is again present within the depth range of interest, thickening southwards from about 40 m in the North Dalton 1 Borehole to 238 m in Claxby No. 1 Borehole in mid Lincolnshire.

The Lias Group is conveniently subdivided into informal 'lower', 'middle' and 'upper' subdivisions based on their lithology. In general terms, the lower and upper subdivisions consist predominantly of siliceous mudstone, whilst the middle unit is predominantly sandstone, siltstone and ironstone with subordinate mudstone. Description of the rock units in the region is conveniently divided into two subregions, north and south of the Market Weighton high.

Cleveland basin (North York Moors, Howardian Hills and the Vale of Pickering)

Five distinct formations are recognised in this area, but only two of these units are recognised as representing a PRTI. They are described in downward succession.

The Whitby Mudstone Formation (formerly Upper Lias) overlies the Staithes Sandstone Formation and is overlain by the Dogger Formation (ferruginous sandstone). It is well exposed on the Yorkshire coast and in deep valleys (inliers) such as Rosedale. It ranges in thickness (Figure 4) from 90 m on the Yorkshire coast, thinning to 43 m in the west (Felixkirk Borehole) (Powell, 1984) to 24 m at Crayke in the Howardian Hills, and is missing entirely over the Market Weighton high (Hemingway, 1974; Powell, 2010). The formation is subdivided into five members, but the uppermost two units are present only in a narrow downfaulted area within the Peak trough (Milsom and Rawson, 1989) in the Ravenscar area. The formation consists of pale grey mudstone and siltstone in the lower part, organic-rich mudstone in the middle part, overlain by fissile siliceous mudstone with calcareous concretions in the upper part.

The Redcar Mudstone Formation (formerly Lower Lias) is well known from exposures on the Yorkshire coast and hydrocarbon exploration boreholes across the North York Moors and the Vale of Pickering. In the west of the area the formation was cored in the BGS Felixkirk Borehole (Powell, 1984) where it is 271 m thick; it thickens eastwards to 275 m near the Yorkshire Coast (Scaling No. 1 Borehole). It thins southwards, as with most Jurassic formations, across the Vale of Pickering and the Howardian Hills to 40 m thick across the Market Weighton high (Hemingway, 1974; Gaunt et al., 1980). The formation consists mostly of fissile, siliceous and calcareous mudstone with thin beds of shelly limestone in the lower part, thin beds of fine-grained sandstone in the middle part, and small pyrite nodules in the upper part.

East Midlands shelf (Market Weighton to Grantham)

The lithology of the Lias Group is similar in this subregion, but there are distinctive differences that have resulted in the group being divided into four subdivisions (formations) of which only the lower two and the uppermost represent a PRTI; the highest formation, the Whitby Mudstone, can be correlated directly with the Cleveland basin. The rocks dip gently (1 to 2º) to the east and are present within the depth range of interest beneath much of the east of the region. A total thickness of 282 m was proved for the Lias Group in the Fulbeck Airfield FB1 borehole north of Grantham and 270 m in the Helpringham No. 1 Borehole (Brandon et al., 1990). The group thins gradually northwards to 200 m near Scunthorpe (Berridge and Pattison, 1994) and, as noted, only the lowermost approximately 40 m are present over the Market Weighton high (Gaunt et al., 1980).

The Whitby Mudstone Formation overlies the Marlstone Rock Formation (ferruginous sandstone) and ranges in thickness from 42 to 54 m in the Grantham area, as proved in exploration boreholes, to about 20 to 30 m near Scunthorpe (BGS Nettleton Bottom Borehole), and is 13 to 38 m thick in the Grimsby area, thinning northwards to the Market Weighton high (Figure 5) where the formation is absent (Gaunt et al., 1992; Berridge et al., 1999). It consists of siliceous mudstone, fissile organic-rich mudstone and silty mudstone with sparse thin limestone beds. The underlying Marlstone Rock Formation is typically only 5 to 7 m thick below south Lincolnshire, but thickens to 11 m near Grimsby. It consists of sandy, shell-fragmental, ooidal ferruginous limestone, and therefore is not a PRTI.

The Charmouth Mudstone Formation (also termed the Brant Mudstone Formation) is 115 m thick in the BGS Copper Hill Borehole near Ancaster (Berridge et al., 1999). In deep boreholes below the Grimsby area, geophysical log signatures indicate an average thickness of 75 m. It comprises mainly fissile, siliceous and calcareous mudstone with abundant phosphatic, ironstone and argillaceous limestone nodules at certain levels. The thin limestone beds that characterise the underlying formation are absent.

The Scunthorpe Mudstone Formation, at the base of the Lias Group, has an average thickness of 113 m. It consists of siliceous and calcareous mudstone with thin beds of argillaceous limestone and calcareous siltstone, particularly near the base and in the upper part. Near Scunthorpe, on the southern flanks of the Market Weighton high, it becomes increasingly ferruginous in the upper part (Frodingham Ironstone Member). In the Grimsby area the formation thins northwards from 90 m in the Tetney Lock Borehole to 70 m in the Winestead Borehole (Berridge and Pattison, 1994); to the west only 45 m were proved in the Cockle Pits Borehole on the southern flanks of the Market Weighton high (Gaunt et al., 1980).

4.2.1.5 Undivided Penarth and the Mercia Mudstone groups (incorporating the Blue Anchor, Branscombe Mudstone and Sidmouth Mudstone formations and the Esk Evaporite Member PRTIs) — LSSR and EVAP

The Triassic Mercia Mudstone Group and the overlying thinner Penarth Group are undivided in the NGS3D model and are hence both described. Together they provide a continuous mudstone-dominated succession that underlies much of the region within the depth range of interest (Kent, 1980; Howard et al., 2008). The rocks dip at about 1 to 2º eastwards (Figures 1, 2 and 3). Together, the groups range in thickness from around 300 m in south Lincolnshire to around 250 m south of the Humber, 250 to 300 m in the Grimsby area, and 200 m in north-east Yorkshire. The unit is overlain by another PRTI, the Lias Group, and is underlain by the Sherwood Sandstone Group (Figure 4). Evaporite rocks, principally gypsum, anhydrite and halite, occur within the lower part of the Mercia Mudstone Group. Below the north-eastern part of the region, including the adjacent offshore area, halite is of sufficient thickness to represent a PRTI (Esk Halite or Röt Halite Member). Unlike the PRTIs within the overlying Jurassic rocks, previously described, the thickness and lithology of the Mercia Mudstone Group was not affected greatly during deposition by the Market Weighton high and, in consequence, it maintains a more uniform thickness in the region.

Principal information sources

The surface outcrop of these rocks is well constrained by geological mapping between Newark and Gainsborough, where superficial deposits are thin and patchily distributed. North of Gainsborough, the outcrop extends below the extensive and thicker superficial deposits to the east of Doncaster, the Vale of York and the area between Northallerton and Middlesbrough. In this northern area, the rock unit is mapped with lower accuracy using evidence from shallow boreholes.

In the subsurface, the unit dips gently between 1 and 3º towards the east or south-east. The Mercia Mudstone and Penarth groups have been penetrated in north Yorkshire and Lincolnshire by many deep exploration boreholes drilled for evaporite minerals, coal and hydrocarbons in the underlying Permian and Carboniferous rocks. Although the density of these deep boreholes declines generally eastwards, they allow the base and top of the unit to be well constrained at depth, mainly by their distinctive geophysical wireline log signatures. The greatest density of deep boreholes is in south Lincolnshire and north-east Yorkshire.

Information on the lithology of the Mercia Mudstone and Penarth groups (Howard et al., 2008) is sourced mainly from surface exposures and from three deep boreholes (Cropwell Bridge; Fulbeck Airfield FB1, and Staithes S20). Additional boreholes in the deeper subsurface to the east provide geophysical wireline logs and borehole drill cuttings that enable the lithological variations, seen at outcrop, to be traced at depth.

Rock type description

In this region, two formations are recognised in the Penarth Group and five formations in the Mercia Mudstone Group. Of these, five are recognised as PRTIs and are described in downward sequence.

The Penarth Group is relatively thin (10 to 20 m thick) and comprises two formations in the region. Exposures are uncommon and most of the information on the Penarth Group comes from boreholes from the Grantham area (Berridge et al., 1999) northwards to the Humber (Gaunt et al., 1992) and north Yorkshire (Powell, 1984); both formations have distinctive geophysical wireline log signatures. The uppermost Lilstock Formation (Cotham Member), 6 to 7 m thick, is represented by pale greenish grey, calcareous mudstone and thin beds of dolomitic sandstone and limestone. The underlying Westbury Formation consists of 4.5 to 12 m of grey to black, very thinly laminated, silty mudstone with a high organic carbon content. Very thin beds of pyritic siltstone and fine-grained sandstone are also present.

The underlying Blue Anchor Formation is consistently 6 to 8 m thick throughout the southern part the region, although up to 18 m were proved in boreholes near Brigg (Gaunt et al., 1992). It is easily distinguished at outcrop and in boreholes by its distinctive greenish grey, dolomitic, silty mudstone and siltstone lithology. Laminated mudstone is also present, especially in the lower part. In the subsurface, the formation is identifiable by its distinctive geophysical wireline log signature.

The Branscombe Mudstone Formation is at least 37 m thick in the Cropwell Bridge Borehole and is 39 m thick in the Fulbeck Airfield FB1 Borehole (Howard et al., 2008) but thins to the south, to 30 m in the Cox's Walk No. 1 Borehole and 16 m in the Hurn Corner Scredington Borehole to the east (Berridge et al., 1999). The formation thickens to the east and north to reach 60 m below the Lincolnshire Wolds, near Brigg. The lithology is similar to the underlying Sidmouth Mudstone, although siltstone and sandstone beds are much less common either as individual beds or composite units. Structureless, blocky beds predominate and laminated mudstones are much less common, generally occurring within the uppermost few metres. In the south-west, near Newark, thick beds of gypsum occur in the upper half of the formation and are quarried for plaster and other industrial uses.

The Sidmouth Mudstone Formation ranges in thickness from 128 m in the south-west of the region (Cropwell Bridge Borehole) (Howard et al., 2008), thickening generally to the east and north-east to 142 m in Lincolnshire (Fulbeck Airfield FB1 Borehole) although it cannot be separated confidently from the rest of the group farther north than the Humber (Gaunt et al., 1992). The formation consists mainly of red-brown siliceous and calcareous mudstone with green patches and thin (up to 4 cm) beds of coarse-grained siltstone and, less commonly, fine-grained sandstone, the latter locally comprising between 10 and 20 per cent of the rock. The thin siltstone and sandstone beds are generally strongly cemented by dolomite and less commonly by silica. At some stratigraphical levels in the south of the region, the hard siltstone/sandstone beds are more common, comprising composite units of five or more closely spaced beds. The mudstone is typically blocky and structureless in texture, but other beds are generally well laminated. Gypsum and anhydrite (calcium sulphate) occur throughout the formation as veins and nodules. Halite is present near the base of the formation in the north-east of the region.

4.2.1.6 Esk Evaporite Member within the Mercia Mudstone Group (= Röt Halite Member offshore) — EVAP

The Esk Evaporite Member (halite) is present in the lower part of the Mercia Mudstone Group in the north-east of the region near Whitby, north-east Yorkshire and southwards to near Withernsea on the coast (Warrington, 1974; Warrington et al., 1980; Riddler, 1981; Howard et al., 2008). Offshore, in the North Sea, the same unit is termed the Röt Halite Member. It is present only in the subsurface in the lower part of the Sidmouth Mudstone Formation, with its base approximately 10 to 20 m above the top of the underlying Sherwood Sandstone Group. The lithology and thickness of the halite is known only from exploration borehole drill cuttings, some cores and the interpretation of geophysical wireline logs (e.g. Cloughton No. 1 Borehole). The member consists of crystalline halite with thin beds of red-brown and grey-green mudstone and siltstone making up about 15 per cent of the thickness of the unit; beds of anhydrite occur near the top. The mapped extent of the member within the depth range of interest is based on Smith (1974b) and Riddler (1981). The member is up to 49.4 m thick (Raymond, 1953) below the Whitby area and is present offshore from there, thinning and pinching out to the west and north of Whitby. It is about 10 m thick below the Malton area, close to its western limit. South of Flamborough Head the member is approximately 10 m thick and it can be traced, at depth, to north of Withernsea where it pinches out (Smith, 1974b). However, the extent and thickness of the halite is based on boreholes often spaced several kilometres apart, and the westernmost limit of the halite may be subject to uncertainty in excess of 2 km. Geophysical wireline log signatures indicate that the unit passes laterally to anhydrite in the Grimsby area (Berridge and Pattison, 1994).

4.2.1.7 ZECHSTEIN GROUP (INCORPORATING THE SNEATON HALITE, BOULBY HALITE AND FORDON EVAPORITE FORMATIONS PRTIS) — EVAP

The Permian Zechstein Group (Figure 3) does not crop out in the region, so knowledge of its distribution and lithology is derived mostly from exploration boreholes for hydrocarbons and evaporite minerals. Additional information comes from exposures, located to the west of the region, from Nottingham northwards to north of Hartlepool, although there is considerable variation from the rock types present at outcrop to those encountered at depth near the north-east Yorkshire coast (e.g. Whitby–Boulby area). The Zechstein Group rocks are highly variable both laterally and vertically. Halite (rock-salt) is subject to plastic flow at depth, which may result in contortion and rapid lateral changes in thickness. At depth in the region the rocks consist of major cycles of limestone and dolomite, followed by variable sulphate (e.g. anhydrite, gypsum, polyhalite) and chloride (e.g. halite, potash) evaporite minerals (Smith, 1974a,b; 1989). In the south of the region the group exhibits gradual thinning, facies changes and the loss of component formations. Three halite rock units are present, in downward succession: the Sneaton Halite Formation, the Boulby Halite Formation and the Fordon Evaporite Formation.

Throughout much of north-east Yorkshire the evaporite (halite) units of the Zechstein Group lie below the lower depth limit (1000 m). However, below the north Cleveland area near Redcar, the Boulby Halite and Fordon Evaporite formations are present within the depth range of interest. These halite-dominated units become thinner (updip) towards the northern margin of the Cleveland basin. Together with the stratigraphically higher Sneaton Halite Formation they thicken offshore from the Redcar area where the Fordon Evaporite Formation reaches up to 286 m thick. The Sneaton Halite Formation is within the depth range of interest approximately 6 km offshore from Robin Hood’s Bay, and is also present approximately 15 km offshore from Scarborough on the flanks of the Scarborough Dome.

At depth below the area around Selby, Goole and Market Weighton, halite beds (11 to 17 m thick) in the Fordon Evaporite Formation were proved in a number of boreholes (e.g. Selby No. 2) within the depth range of interest (Smith, 1974b; Smith, 1989; Gaunt, 1994). Hereabouts, it consists of grey halite with subordinate beds of red mudstone and anhydrite; halite makes up about 75 per cent of the formation (Smith, 1974a; 1974b; Gaunt, 1994). The formation dips eastwards between 2 and 3º, and consequently passes below the lower depth range of interest (1000 m) below the Yorkshire Wolds.

Principal information sources

These rocks are known solely from exploration boreholes for evaporite minerals and hydrocarbons, including the Kirkleatham No. 2, Staithes No. 1, Cloughton No. 1 and Robin Hood’s Bay No. 1 boreholes. Information on the thickness and lithology comes from cores, cuttings and distinctive geophysical wireline log signatures, and from mine workings in the Boulby area. Geophysical seismic profiles provide additional information on the subsurface areal distribution of the rock types.

Rock type description

The Sneaton Halite Formation is separated from the stratigraphically older Boulby Halite Formation by 10 to 20 m of intervening strata. Where present beneath the region, the formation lies just below the depth range of interest. It is up to 55 m thick in the Whitby area (Smith, 1974b) but thins rapidly westwards and is absent below Wilton and Teesside (e.g. Hayton Well No. 1 Borehole). The nature of its western limit is poorly known, and its absence beyond this limit may be due to dissolution of the salt at depth. The formation can be traced in boreholes southwards below the Yorkshire Wolds where it is about 35 m thick, but the formation thins to zero in a line oriented approximately north–south, between 20 to 40 km from the Yorkshire coast (Smith, 1974b). The lithology is well known from cores in boreholes drilled near Aislaby and Sleights (e.g. Sleights 6A6; Smith, 1974a; 1974b). The lower part (13 to 19 m thick) consists of halite with thin laminae of anhydrite and anhydritic mudstone. This is overlain by a bed of potash (up to 8.5 m thick), which in turn is overlain by halite and red mudstone (16 to 25 m thick), the latter making up to 90 per cent of the rock.

4.2.2 Older sedimentary rocks

4.2.2.1 WARWICKSHIRE GROUP (INCORPORATING THE ETRURIA FORMATION PRTI) — LSSR

The Warwickshire Group does not crop out in the region, but has been proved at depth (Figures 2 and 3) in hydrocarbon exploration boreholes (e.g. Fiskerton No. 1 and Cotmoor Lane boreholes) in the area adjacent to the south-west margin of the region (Pharaoh et al., 2011). It is also present farther north in the Grantham–Sleaford area (Berridge et al., 1999). In this region the group comprises two formations, the Halesowen Formation and the underlying Etruria Formation, which in turn overlie the Pennine Coal Measures Group. The Halesowen Formation is overlain unconformably by Permian strata or the Sherwood Sandstone Group. Farther north, below Lincolnshire, the Yorkshire Wolds and north-east Yorkshire, there is little evidence for the presence of the group; coal exploration boreholes in the Humber area (North Ewster and Butterwick boreholes; Gaunt et al., 1992) and the Cleethorpes No. 1 and Tetney Lock No. 1 boreholes south of Grimsby (Berridge and Pattison., 1994) indicate that hereabouts the highest Carboniferous beds underlying Permian strata are represented by the Pennine Coal Measures Group.

The group consists predominantly of red and green mudstone and siltstone with beds of medium- and coarse-grained sandstone. Thick units of mudstone characteristic of the Etruria Formation in type area in the West Midlands (Powell et al., 2000), where it is worked for brick clay, are not present at depth in this region. Consequently, the unit may not represent a suitable PRTI. However, the group is described for completeness.

Principal information sources

The group is known only from coal and hydrocarbon exploration boreholes in the south and east of the region around Sleaford and Grantham (Berridge et al., 1999; Pharaoh et al., 2011). To the north in Lincolnshire and Yorkshire the group is cut out beneath the overlying Permian or Triassic rocks. Information on the lithology is derived from borehole cores, cuttings and distinctive geophysical wireline log signatures.

Rock type description

The Halesowen Formation was cored in coal exploration boreholes around Sleaford (Mareham Grange; Hurn Corner Scredington; Burton Lodge, and Ruskington boreholes) and extending south-westwards over a distance of about 30 km to the Grantham area (Berridge et al., 1999). It consists predominantly of medium- to coarse-grained, micaceous sandstone generally about 35 m thick, but reaches a maximum of 80 m in the Gables Farm Borehole (Berridge et al., 1999). Thin beds of mudstone and siltstone are present in some of the boreholes, but they are of insufficient thickness to be of interest as a PRTI.

The underlying Etruria Formation was also proved in the boreholes as noted and is included as a PRTI. It was fully cored in the Mareham Grange and Hurn Corner Scredington boreholes where the formation (25 to 36 m thick) overlies the Pennine Coal Measures Group. The lower part (up to 25 m thick) is dominated by medium- to coarse-grained sandstone, conglomerate and breccia with thin mudstones. The upper part is mudstone-dominated, consisting of up to 13 m of interbedded siliceous mudstone and siltstone with sparse thin coals and seatearth clays. As noted previously, there is a high ratio of sandstone to red mudstone in this region.

4.2.3 Basement rocks

Higher strength rocks (lava and granite) are known to be present within the depth range of interest only in the south of the region (Figures 4 and 17), between Grantham and The Wash (Berridge et al., 1999; Pharaoh et al., 2011). Evidence for the lithology comes from exploration borehole cores and cuttings, as well as geophysical wireline logs. The spatial distribution of the lava and granite, at depth, is based on seismic refraction and geophysical (gravity and magnetic) potential field data (Pharaoh et al., 2011).

4.2.3.1 ORDOVICIAN LAVA (INCORPORATING INTRUSIVE ANDESITE AND DACITE IGNEOUS ROCKS) — HSR

A number of small igneous rock units of probable Mid Ordovician age have been delineated eastwards from the Grantham area to The Wash (Figure 11), but most of these lie below 1000 m depth (Pharaoh et al., 2011). However, on a subsurface structure known as the Foston high, the Cox's Walk No. 1 Borehole proved about 243 m of andesite and dacite lava with minor rhyolitic lavas in the upper part, unconformably overlain by early Carboniferous limestone. The top of the lavas lies at 566 m depth and the lavas were not bottomed at about 800 m depth. The lavas are well jointed and fractured; they show chloritic alteration and are cut by veins bearing calcite and pyrite. Similar rock types were proved in the Great Osgrove Wood Borehole located about 20 km to the south-east. Based on geophysical data, the lateral extent of the lavas proved in the Cox's Walk No. 1 and Great Osgrove Wood boreholes suggests an elongate, north-west-trending area extending about 10 km wide by about 35 km in length (Pharaoh et al., 2011) (Figure 17).

4.2.3.2 GRANITE (INCORPORATING INTRUSIVE IGNEOUS ROCKS PRTI) — HSR

Geophysical gravity and magnetic surveys below The Wash and adjacent areas in the region (Figure 17) indicate that this area is underlain at depth by granite (the putative Wash batholith) to within about 1000 m of the surface in the vicinity of the Sibsey No. 1 Borehole (Pharaoh et al., 2011). Although The Wash granite has not been proved by boreholes, the Claxby No. 1 Borehole, near Horncastle, proved sodic microgranite at 1482 m depth, overlain by the Pennine Coal Measures Group (Pharaoh et al., 2011). Geophysical modelling suggests that the upper, undulating surface of the granite rises to the south, so that in the Boston area it is present over a wide area with its upper surface at about 830 to 1074 m depth (Figure 17).

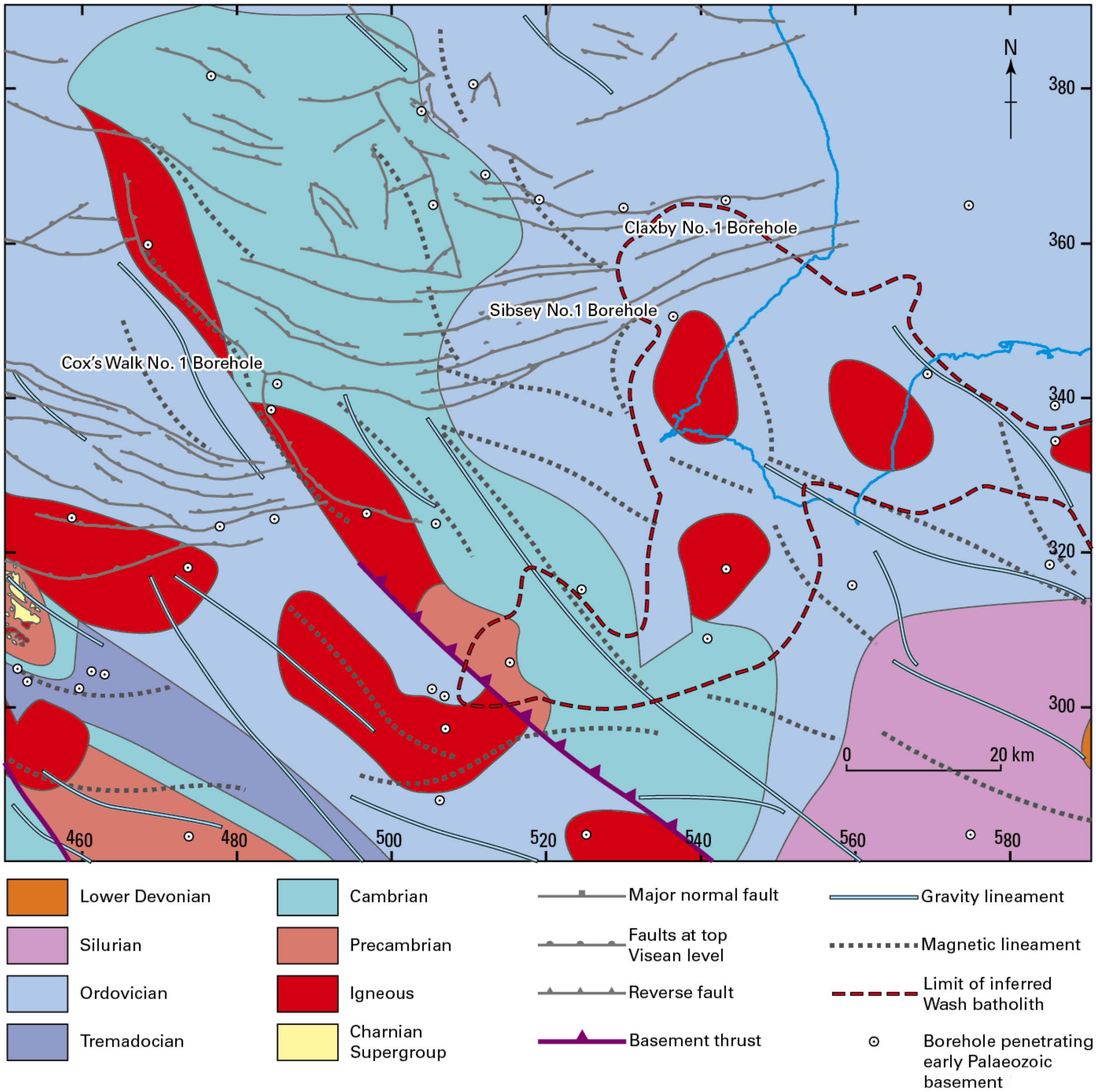

Figure 17 Map showing the information on the Caledonian basement structure and lithology at depth based on geophysical and borehole data in the south of the region (from Pharaoh et al., 2011). The subsurface limit of the inferred Wash batholith is shown by the dashed red line. British Geological Survey © UKRI 2018.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in Eastern England 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 structure's extent in the depth range of interest and to output them as ArcGIS shape files to produce maps. The guidance sets the depth range of interest for emplacement of a GDF between 200 and 1000 m below NGS datum and defines this as the depth range in which rock structures should be assessed. In the following discussion some reference is made to rocks and structures below the depth range of interest in order to clarify the structural setting of the region. The map highlights only those faults that were considered in the depth range of interest.

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

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

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

Compared to surrounding regions, the nature of the basement and deep structure of the Eastern England region is very poorly known and a matter for considerable conjecture (e.g. see Turner, 1949; Pharaoh et al., 1987; Woodcock, 1991). In part this is a result of a paucity of deep boreholes penetrating the basement of the region. In the south and central part of the region, the Caledonide basement is deeply buried by a thick pile of strata ranging in age from Carboniferous (older sedimentary cover) to Permian, Triassic, Jurassic and Cretaceous (younger sedimentary cover). These cover designations are equivalent to the text descriptors 'older sedimentary bedrock' and 'younger sedimentary bedrock' respectively (see Figure 3). The limited basement borehole samples available are interpreted by Pharaoh et al. (1987) and Pharaoh et al. (1991; 1993) as a low-grade metasedimentary and metavolcanic complex of early Palaeozoic age related to the development of the Tornquist branch of the European Caledonides overlying an Avalonian basement referred to as the Fenland Terrane (Pharaoh and Carney, 2000). Various lines of evidence, including the trend of geophysical magnetic and gravity potential field anomalies (Lee et al., 1990) and the Caledonide metamorphic zonation (Pharaoh et al., 1987; Merriman et al., 1993), as well as the inferred basement inheritance in the sedimentary cover (Pharaoh et al., 2011), have been used to infer the presence of an underlying north-north-west-trending basement grain. Several of the Tournaisian–Visean basin-controlling faults have this trend (Pharaoh et al., 2011). The most significant lineaments within the region are the 151 km-long north-west trending South Craven–Morley–Campsall–Askern–Spital fault zone which extends into the region from the west and the over 175 km-long west–east trending North Craven–Howardian Hills–Vale of Pickering–Flamborough Head fault zone, which extends offshore into the Southern North Sea basin.

The region lies to north of the Midlands microcraton (Wills, 1978; Pharaoh et al., 1987; Lee et al., 1990; Smith et al., 2005; Chadwick and Evans, 2005) as a basin formed by extension during early Palaeozoic times, associated with the development of the deep Welsh and Anglian Caledonide basins. After several phases of subsidence in Cambrian to Silurian times (Molyneux, 1991; Woodcock and Pharaoh, 1993), this basin was inverted during the Acadian phase of the Caledonian orogeny in Early Devonian (about 395 Ma) times.

In Early Devonian times the region lay within the southern margin of the Laurussian continent and came to form part of the Variscan foreland. A tensional regime was established in the Variscan foreland in Late Devonian (Frasnian–Fammenian) times and the development of a series of linked half-graben was initiated. Three main late Palaeozoic depocentres, controlled by major syndepositional normal faults, impinge on the southern part of the region. These are the Gainsborough trough in the centre and the Sleaford and Coningsby graben complex in the south-east, while the Widmerpool half-graben lies just beyond the south-western limit of the region. These basins developed as a consequence of north–south directed extension in the Variscan foreland (Leeder, 1982). Most of the basins therefore have a broadly west–east orientation, although the geometry of some, e.g. the south-east trending Gainsborough trough, has been very strongly influenced by the reactivation of local Caledonide basement structural grain. Individual components within the Gainsborough trough have a dominantly north-west orientation, as a consequence of the strong influence of reactivated structures (thrusts etc.) within the basement, here inferred to be related to the closure of the early Caledonian Tornquist oceanic basin (Pharaoh et al., 1995; Smith et al., 2005). On its north-east side, the Gainsborough trough is controlled by the Askern–Spittal Fault, with major Tournaisian–Visean normal downthrow to the south-west.

Far to the south, progressive closure of the ocean basins within the Armorican terrane assemblage during the late Carboniferous resulted in pulses of compressional deformation and flexural subsidence of the Variscan foreland, of which the region formed part. Original Tournaisian–Visean extensional faults were reactivated in a reverse sense at this time. The style and magnitude of fault reversal and basin inversion depends on the orientation of the faults and that of the basement faults that underlie them. The most prominent inversion anticlines are associated with north-west trending structures such as the Eakring Anticline and Nocton Fault.

Following consolidation of the supercontinent of Pangaea in the Variscan Orogeny, in latest Carboniferous times, significant erosion of the orogen occurred with extensional collapse and regional subsidence following decay of the lithospheric thermal anomaly. The main developing extensional graben systems, however, lay to the west (e.g. Worcester graben) or east (Sole Pit trough) of the region.

In Jurassic times, the region was partitioned into two structural regimes. In the south and central parts, the eastern England platform was relatively buoyant in the Jurassic and also escaped the end-Cretaceous inversion that affected the Cleveland basin in the north of the region, and the offshore Sole Pit trough to east. Both of the latter areas contain much thicker Jurassic and Early Cretaceous strata than the platform. The developing Alpine orogenic belt reached the western Alps in Late Cretaceous times (Stampfli and Borel, 2002). This convergence induced compressive stresses to the lithosphere of the Alpine foreland, resulting in early inversion of graben structures such as the Weald and Cleveland basins. Post-Jurassic movements can be demonstrated on a number of faults within the region, both in the south and in the Vale of Pickering–Flamborough Head fault zone in the north.

The dominant structural influences in the Cenozoic were the Palaeogene development of the Iceland Plume, associated with the onset of sea-floor spreading between Europe and Greenland, and the Neogene Alpine continental convergence to the south, associated with progressive development of the Alpine–Carpathian orogen. The region lay in the foreland of the latter and was affected by a number of pulses of inversion throughout this time. The final, Savian (end Oligocene/Early Miocene) pulse of the Alpine orogeny caused significant uplift in the Sole Pit (Glennie and Boegner, 1981; Pharaoh et al., 2010) and Cleveland basins (Whittaker, 1985).

A review of the tectonic evolution of the UK is provided in the National Geological Screening: Appendix A (Pharaoh and Haslam, 2018).

5.3 MAJOR FAULTS

The major faults selected from analysis of the UK3D National Geological Model (Waters et al., 2015) and published maps in the region (Figure 18) exhibit a variety of orientations and evolutionary histories, as a consequence of the complex structural history described. In the UK context, fault systems and complexes exceeding 100 km in length, and usually associated with clear geophysical (e.g. gravity and magnetic potential field) signatures, are referred to as lineaments. Although these are relatively rare, they are of considerable interest because they commonly bound crustal blocks with different physical properties and history (‘terranes’ in the broadest sense of the definition) and may have a demonstrably long history of reactivation.

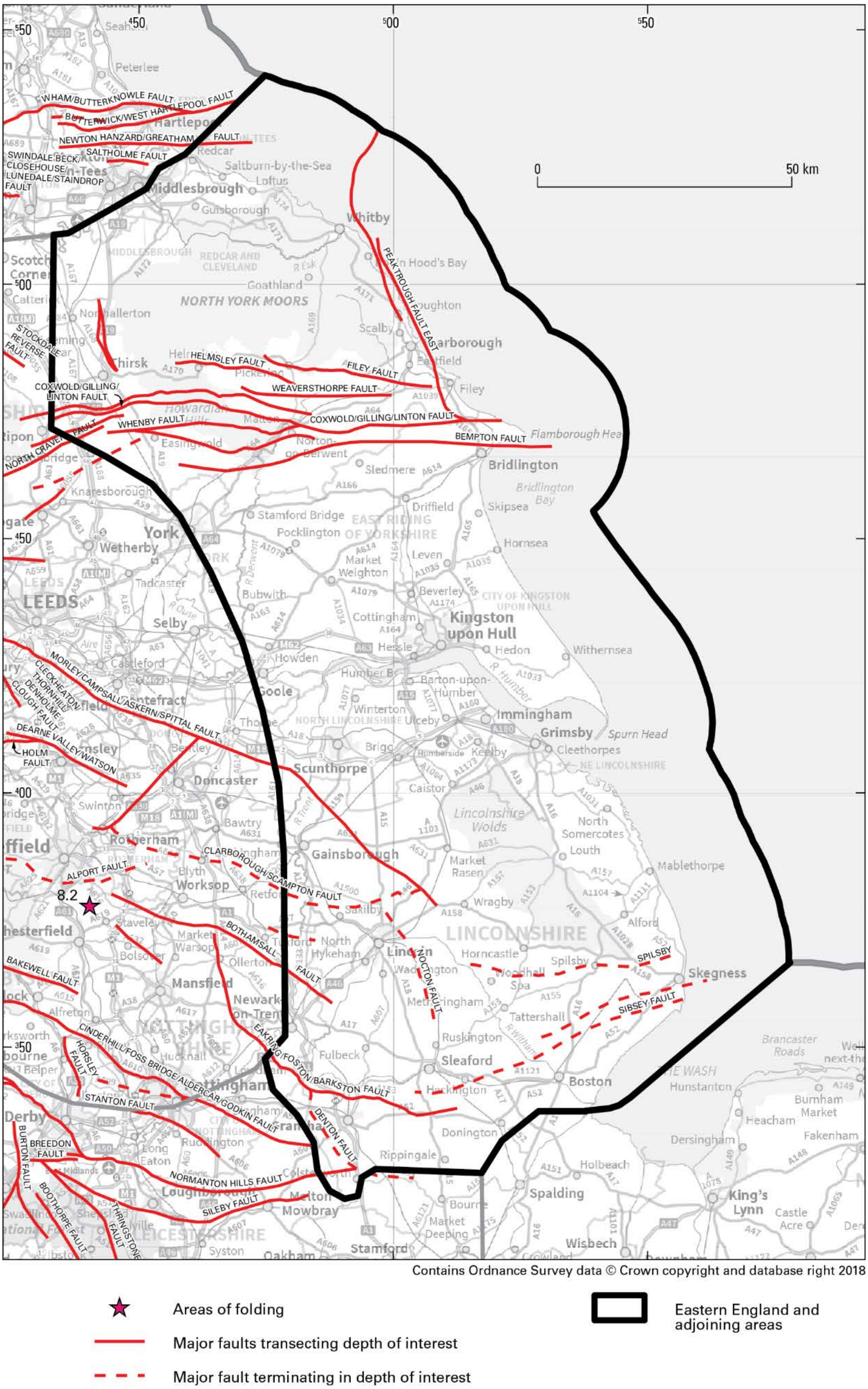

Figure 18 Map of the major faults in the Eastern England region. No areas of intense folding have been identified. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

5.3.1.1 SOUTHERN AREA

In the south and central part of the region, the Caledonide basement is deeply buried by a thick pile of strata ranging in age from Carboniferous (older sedimentary cover) to Permian–Cretaceous (younger sedimentary cover), with markedly different structural characteristics. The South Craven–Morley–Campsall–Askern–Spital fault zone, with its 151 km mapped length, extends into the region from the north-west. The fault zone is developed almost entirely at the Carboniferous stratigraphical level. It separates downthrown basins in the south (the Bowland basin and Huddersfield basin outside the region, and the eastern part of the Gainsborough trough in the region) from a very persistent high (Askrigg block–Askern–Spital high) in the north. The latter is underpinned by the Wensleydale Granite of inferred Ordovician age (Pharaoh et al., 1997) and the postulated Market Weighton Granite (Bott et al., 1978). Thus, even if the lineament was not actually initiated by deformation during the Caledonian orogeny, its development was certainly influenced by granites emplaced around that time. The Askern–Spital Fault defines the north-east edge of the Gainsborough trough and the Lincoln platform, against the Askern–Spital high (Kent, 1980), and the normal downthrow at the base of the older sedimentary cover is about 2000 m in the region, decreasing to 200 m at the top of the older sedimentary cover (Pharaoh et al., 2011). The fault is associated with a double bend in the Lincolnshire Limestone scarp, and local excision of Mid Jurassic strata suggest penecontemporaneous movements of that age (Kent, 1980). The southernmost part of the Humberside platform lies beyond the Askern–Spital Fault, at the northern extremity of the region. The Brigg Fault and its extension to the west-north-west lies subparallel to the South Craven–Morley–Campsall–Askern–Spital fault zone, and 16 km to the north of the latter. Seismic data suggest that its downthrow in the older cover is rather limited, much less than that of other regional structures, but it does deflect both the Jurassic and Cretaceous outcrops (Kent, 1980), indicative of more recent movement.

A widening of the Lincolnshire Limestone outcrop in the Nocton area south of Lincoln is coincident with a deep-seated pre-Permian structural high (Nocton high), which seems to have been intermittently buoyant during the Jurassic (e.g. during deposition of the Middle Lias and Lower Lincolnshire Limestone). Over this uplift the Carboniferous rocks are much thinner than in the basins to the east and west, and marked magnetic and gravity anomalies indicate that the dense basement rocks are relatively shallow here. The north-north-west-trending Nocton Fault defines the eastern edge of the high, and has a normal downthrow of 200 to 300 m at the top of the older sedimentary cover level to the north-east (Pharaoh et al., 2011). The southern bounding fault of the Gainsborough trough was initially the Beckingham Fault. Subsequently, fault control shifted to the Clarborough–Scampton Fault, some 7 km farther south (Fraser and Gawthorpe, 2003). This has northward normal downthrow of older sedimentary cover strata exceeding 300 m, identified in the UK3D national geological model (Waters at al. 2015). In late Namurian times, mild reactivation of earlier normal faulting occurred, particularly in the eastern part of the basin e.g. the north-east-trending Scampton Fault (Fraser and Gawthorpe, 2003). The Lincoln platform lies at the southern margin of the Gainsborough half-graben and is contiguous with the south Humberside platform. It includes important oilfields such as Welton and Nettleham, which are developed in a north-north-west-trending belt of Variscan inversion anticlines.

The Sleaford half-graben lies in the hanging wall of the Barkston Fault. Seismic reflection lines oriented north–south across the Foston high (the footwall of the fault) and Sleaford Low demonstrate early syndepositional normal displacement of the older sedimentary cover on the Barkston Fault, with marked thinning of the sequence northward onto the hanging wall dip slope. As with other major basin-controlling faults in the region, the displacement of the basal older sedimentary cover strata is much larger, exceeding 1400 m, than at the top. The Sleaford half-graben may be regarded as a small-scale analogue of the Widmerpool half-graben, offset from the former to north-east of the Foston high. They are separated by the Eakring–Denton Reverse Fault with up to 300 m of Variscan reverse movement, which probably reflects Carboniferous reactivation of a thrust fault or shear zone within the Caledonian basement. Syndepositional growth of older sedimentary cover strata is also present. The Coningsby half-graben is contiguous with the Sleaford half-graben, but shows the opposite polarity. The northward normal downthrow on the Sibsey Fault is large (Pharaoh et al., 2011) at the base of the older sedimentary cover strata (>1000 m) but decreases considerably eastward, where in any case it falls below the 1000 m maximum depth range of interest. Seismic data suggest the presence of a tilt block dipping northwards, controlled by a syndepositional normal fault with southward downthrow, the Stixwould Fault, on the northern margin of the graben. Again, the eastern part of this fault, with large throw of the older cover sequence, falls below the 1000 m depth range of interest. Unfortunately the seismic data in this part of the region, with thickening of the younger sedimentary cover towards the North Sea basin, are badly affected by multiple reflections so the base of the graben is not well imaged.

Seismic reflection data indicate the presence of at least 2000 m of older cover in the hanging wall of the north-east dipping Eakring Fault for which syndepositional normal displacements are inferred (Chadwick and Evans, 2005). The fault displays a reverse throw of 250 m of the older cover, a consequence of Variscan inversion, which was concentrated on faults with a north-west and north-north-west trend in the eastern part of the region. The base of the younger cover is offset by a normal throw of about 60 m (Pharaoh et al., 2011). The Denton Fault delimits the western edge of the Foston high. It represents a continuation of the Eakring lineament to the south-east, and ultimately links to the basement Glinton Thrust, beyond the region near Peterborough (Chadwick and Evans, 2005). The Denton Fault effectively represents a transfer zone between the Widmerpool and Sleaford half-graben, which are offset en échelon by it. Seismic data indicate that the fault dips to the north-west beneath the high (Pharaoh et al., 2011). Pre-Carboniferous basement of the Foston high is uplifted about 500 m compared to the regional level to the west. On the Eastern England platform, the average regional dip of the younger cover is 1.25^{o} to east, locally steeper in the vicinity of major faults. Some of the Variscan faults were reactivated and show minor amounts of normal movement affecting the lower part of the younger cover, e.g. the Eakring Fault (up to 60 m northward downthrow of base Permo-Triassic) and the Barkston Fault, with northward downthrow of the base Permian and base Jurassic strata by up to 40 m (Pharaoh et al., 2011).

5.3.1.2 NORTHERN AREA

The North Craven–Vale of Pickering–Flamborough Head fault zone is a braided fault complex with a west–east trend, comprising a wide zone of sinuous, intersecting and *en échelon* faults. It has a total mapped length exceeding 175 km, extending from the southern side of the Askrigg block to the Dowsing–South Hewett fault zone of the Southern North Sea basin (Chadwick and Evans, 2005). This major lineament separates the Cleveland basin, containing thick sequences of both older and younger cover in the north, from the Mesozoic Eastern England platform (and underlying Palaeozoic Market Weighton high) in the south. These two tectonic provinces had very different structural histories. The Cleveland basin, a major downwarp in the early Carboniferous and Jurassic, was inverted in both end-Carboniferous and end-Cretaceous times. Listric-style faulting with shallow detachment of the younger cover is common in areas with thick Permian salt. A mainly mid Cenozoic age for the folding of Cleveland was formerly assumed from physiographical evidence, but the displacement of the Cenozoic surface is on a much smaller scale than the amplitude of the main Cleveland fold (Kent, 1980), an interpretation supported by mapping offshore (Dingle, 1971). The northern end of the Eastern England platform is underpinned by the notably rigid Market Weighton high (Kent, 1980). This southern area was relatively buoyant in the early Carboniferous and Jurassic, but escaped the end-Carboniferous uplift and also the end-Cretaceous inversion which affected the Cleveland basin and the offshore Sole Pit trough.

Beyond the western limit of the region, the North Craven Fault defines the southern edge of the Askrigg block, underpinned by the Wensleydale Granite. The constraints on any possible early Palaeozoic movements on the fault system are poor, as with the South Craven Fault reviewed previously. It was certainly a zone of strong Variscan inversion with reactivation in Permo-Triassic times. The west-south-west- trending Howardian Hills fault belt affects Permo-Triassic strata at crop. The belt comprises fault pairs with arcuate and sinuous surface traces on the northern side (implying low angle dips to south) and straighter traces on the southern side (hence steeper dips to north). Many of the faults have the form of flower structures, and this, together with the relatively small net vertical displacement between the marginal blocks, implies dominantly transcurrent displacement. The Whenby Fault links the Howardian Hills faults to the eastern part of the system. The Helmsley and Filey faults define the northern edge of the Vale of Pickering–Flamborough Head fault zone. These faults juxtapose Corallian Group strata to the north against Late Jurassic clays in the south, a southward normal downthrow exceeding 300 m (UK3D model). However, apparent absence of rollover at this level supports the contention of Kent (1980) that intra-Jurassic extension was minimal. Farther west, the Weaversthorpe Fault, parallel to the Filey Fault, shows comparable throw (about 400 m) of the Late Jurassic strata, but becomes listric with depth, and detaches in Permian evaporites (Chadwick and Evans, 2005). Associated antithetic faulting leads to the development of narrow but relatively deep asymmetric graben features, such as the Assenby–Coxwold graben (Chadwick and Evans, 2005). The Bempton Fault, concealed by the Chalk Group beneath Flamborough Head, downthrows about 500 m to the south and also has markedly listric form with rollover folding. Seismic evidence suggests that this is a characteristic of many of the faults in this zone.

The relationships described suggest that the main period of normal fault movement was in Late Jurassic or Early Cretaceous times (Chadwick and Evans, 2005). Minor upwarping of the Chalk Group is attributed to Cenozoic basin inversion, associated with the Alpine orogeny. In addition, zones of faulting associated with narrow graben on a northerly trend are notable. Just off the coast to the north-east, the north-north-west-trending Peak trough fault zone is associated with local normal downthrow of 229 m. The Kirby Sigston–Knayton graben lies at the western end of the Cleveland basin (Frost, 1998; Powell et al., 1992). The base of the Jurassic is downthrown by 200 m by the western fault of this pair, but the base of the younger cover is not displaced, reflecting detachment in the overlying evaporitic strata. Chadwick and Evans (2005) attribute the development of such spectacular but quite localised structures to gravity sliding down a low gradient regional palaeoslope, probably in post-Jurassic times.

The Cleveland Dyke of Yorkshire is the south-eastern portion of one of the basaltic dykes related to the Tertiary igneous complex of Mull. This intrusion, while not a fault, is described here because it has the potential to form a conduit for fluid flow across stratigraphical boundaries. The dyke is almost certainly contiguous at depth with the Armathwaite Dyke of Cumbria, which can be traced north-westwards on the aeromagnetic map across the Solway Firth. Within the region the dyke cuts Triassic and Jurassic rocks and is up to 25 m wide. It is first seen in the north near Eaglescliffe Station in the Tees Valley and can be followed south-eastwards in a series of *en échelon* outcrops for about 50 km to Fylingdales Moor.

5.4 FOLDING

Within the Cleveland depositional basin, the North York Moors coincide with a general east–west- trending broad arch that carries subsidiary domes (Chop Gate, Danby Head, Eskdale and Robin Hood's Bay) (Kent, 1980). Near the Yorkshire coast, north–south trends are notable and minor structures, e.g. the Eskdale Anticline, produce segmentation of the main Cleveland Anticline (Kent, 1980). None of these can be considered tight folds with steep limbs in the context of the present report. On the Eastern England platform, the average regional dip of the younger cover is 1.25° to east, locally steeper in the vicinity of major faults. In the Carboniferous strata, dips rarely exceed 10°, except where they are locally involved in Variscan inversion structures, where they may steepen to 25 or 30°.

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 that attend their mapped position at the surface.

Faults are planes of movement along which adjacent blocks of rock strata have moved relative to each other. They commonly consist of zones, perhaps up to several tens of metres wide, containing several to many fractures. The portrayal of such faults as a single line on the geological map is therefore a generalisation.

The presence of faults, and their subsurface location, attitude and displacement, 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 data (gravity and aeromagnetic) 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 faults and other structures in the subsurface. Seismic lines cover most of the Eastern England region with reduced coverage in the north and south of the region, hence the recognition and location of subsurface faulting and folding carries higher confidence and is better constrained than many other regions under review. Principal uncertainties in seismic location depend on the spacing and quality of the seismic grid, migration (or not) of the data and depth conversion of the interpretation. Experience shows that under good conditions, the following uncertainties should apply:

- XY location: better than 50 m
- Z depth at 1000 m: about 50 m
- 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 Eastern 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 EASTERN ENGLAND

Across the region there is limited information related to groundwater, either in terms of groundwater movement or chemical composition, in the depth range of interest. Almost all the available information is related to the relatively shallow groundwater system that is currently exploited for groundwater resources to depths typically less than 100 m.

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The regional groundwater flow system in the region is controlled by a range of factors: the broad distribution of geological units and the regional geological structure; the hydrogeological characteristics of those units; topography and hence the distribution of recharge and other hydraulic boundary conditions, such as the coastline of the North Sea to the east of the region.

The GVS for the Eastern England region (Table 3) divides rock units into younger sedimentary rocks, older sedimentary rocks and basement rocks and lists the principal aquifers. Across the region only the post-Permian sedimentary cover rocks are exposed (Figure 3) and consequently subject to direct groundwater recharge. As these rocks broadly dip east or north-east, or south-east (Figures 3, 4 and 5) regional groundwater flow in these units is dominantly down-dip towards the North Sea. This flow is primarily driven by head gradients between recharge occurring over areas of higher ground across the region, such as the North York Moors, Yorkshire Wolds and Lincolnshire Wolds, and the constant head imposed by the North Sea to the east of the region. Note that the Triassic Sherwood Sandstone Group crops out in the north-west of the region (Figure 16) but that recharge to this unit will primarily take place in the adjacent Pennines region. No direct recharge occurs to the Carboniferous sedimentary cover or basement rocks across the region, and no head observations are available in the reviewed literature for these geological units. Consequently, there is no direct evidence for regional-scale hydraulic boundary conditions or regional flow directions in these units.

The overall hydrostratigraphy of the region is conceptualised as following the GVS and consists of four broad groupings:

- a groundwater system in the younger sedimentary rock sequence above the Mercia Mudstone Group, consisting of Cretaceous- to Triassic-aged sediments
- the regionally confining Mercia Mudstone Group
- a groundwater system in the younger sedimentary rock sequence below the confining Mercia Mudstone Group and above the Carboniferous–Permian unconformity
- a deep groundwater system consisting of older, Carboniferous sedimentary cover and the basement rocks

The deepest groundwater system is the confined basement rocks, and the older, Carboniferous sedimentary cover rocks. These units are separated from a highly hydrogeologically variable younger sedimentary cover sequence by a major regional unconformity. There is no information in the reviewed literature to assess the hydrogeological implications of this unconformity. The hydrogeologically varied younger cover sequence above the Carboniferous–Permian unconformity includes:

- principal aquifers of variable regional significance, including
  - the Chalk Group
  - Spilsby Sandstone Formation
  - Brantingham Member of the West Walton Formation
  - Corallian Group
  - Blisworth Limestone Formation
  - Cornbrash Formation (part of the Great Oolite Group)
  - Lincolnshire Limestone Formation (part of the Inferior Oolite Group)
  - Sherwood Sandstone Group, and Zechstein Group limestones
- units with varying hydrogeological characteristics including a regionally confining unit, the Mercia Mudstone Group
- aquitards such as the mudstones of the Ancholme Group and sequences of evaporites (including those in the Permian Zechstein Group).

This younger cover sequence is conceptualised as consisting of three broad hydrogeological units, i.e. the sequences above and below the regionally confining Mercia Mudstone Group and the Mercia Mudstone Group itself.

Most of the depth range of interest across the region is occupied by sediments of the younger cover sequence, i.e. the upper three groundwater systems. Potential pathways for groundwater movement between units within the sequence are provided by overstepping of formations or lateral facies variations associated with regionally significant structures such as the Market Weighton high (Figure 10). There are many faults in the region (Section 7), and some with large throws juxtapose strata with contrasting hydrogeological characteristics and/or themselves impart hydraulic anisotropy into the sequence; others act as conduits. There are also potential routes for movement of groundwater between the groundwater systems via anthropogenic structures at depth (e.g. boreholes and mines). These potential pathways for groundwater movement are discussed after a description of the four hydrogeological units in the following sections.

6.3.1 Hydrogeology of the younger sedimentary cover above the Mercia Mudstone Group

The upper groundwater system above the Mercia Mudstone Group is a thick sequence of relatively young cover rocks ranging in age from the Cretaceous Chalk Group at the top of the sequence to the Triassic Penarth Group at the base of the sequence. The units broadly dip eastward across the region. All are exposed at the surface, and so receive recharge, and all are present in the depth range of interest. Groundwater flow in this upper groundwater system is primarily driven by head gradients between recharge occurring over areas of higher ground across the region and the constant head imposed by the North Sea to the east of the region.

The sequence of younger cover rocks is not regionally confined, and consequently, unlike the groundwater system below the Mercia Mudstone Group, it has been subject to more prolonged and deeper circulation of fresh groundwaters. However, there are still variations in the hydrogeological characteristics of the sequence with depth due to the varying nature of the overburden. In addition, the sequence is very lithologically variable and this also influences the hydrogeological characteristics of the individual units within the groundwater system. As with all groundwater systems in the region, most hydrogeological information is available for the depth range of active hydrogeological exploitation, typically less than 100 m.

The upper groundwater system can be divided into four subdivisions on the basis of the hydrostratigraphy:

- Late Cretaceous Chalk aquifer and Early Cretaceous rocks
- Mid and Late Jurassic sedimentary rocks
- Lias Group
- Triassic Penarth Group

6.3.1.1 Late Cretaceous Chalk aquifer and Early Cretaceous rocks

The Chalk aquifer

The Chalk Group forms the most important aquifer in the region (Kent, 1980). As with many other units in the region, almost all the hydrogeological information is related to the relatively shallow groundwater system, which is currently exploited for groundwater resources.

The Lincolnshire Chalk Group is found within the depth range of interest only close to the coast. In Yorkshire it is above the interval of interest in the north of the area. The Chalk aquifer system is unconfined beneath the Lincolnshire Wolds, but is locally confined by glacial till in most of the eastern part of the region. Recharge occurs on the Wolds, from where groundwater generally flows to the north-east, discharging naturally as springs at the western edge of the till and to the sea (Whitehead and Lawrence, 2006). In Yorkshire, the Chalk Group is buried and locally confined by Quaternary deposits in the eastern part of the region, mainly by glacial tills, sands and gravels, and Holocene (postglacial) coastal and marsh sediments (Gale and Rutter, 2006).

The Chalk Group is generally directly underlain by the Early Cretaceous Hunstanton Formation. In Lincolnshire and the area immediately north of the Humber, it oversteps a sequence of Jurassic and Early Cretaceous formations, which are of variable permeability. Hydraulic continuity between the Chalk Group and more permeable early Cretaceous formations is assumed where they are in direct contact, but this is difficult to prove. Such continuity is certainly spatially variable and probably relatively low flux compared to that of the Chalk Group itself. Nonetheless these zones of contact may provide pathways for groundwater movement between units. Whitehead and Lawrence (2006) states that the permeable early Cretaceous formations that underlie the Chalk Group form part of the Lincolnshire Chalk aquifer system, although the degree of hydraulic connectivity is variable. When considering this aquifer system, the base is the low permeability clays, the Ancholme Group in Lincolnshire (Whitehead and Lawrence, 2006) and this or the Early Jurassic clays in Yorkshire.

The regional groundwater flow direction is broadly downdip to the north-east in Lincolnshire and to the east in Yorkshire, but in the confined aquifer, piezometry may be influenced by abstractions. Allen et al. (1997) notes that the hydraulic gradient in the confined Chalk is very shallow, but is steeper in the Wolds, where it mirrors the topography. Little flow through the Chalk is thought to occur from the recharge zone to the confined zone south of Louth, in Lincolnshire, where Quaternary erosion separated the Wolds from the confined Chalk (Allen et al., 1997). The Chalk aquifer is artesian in parts of the confined aquifer (Gale and Rutter, 2006; Whitehead and Lawrence, 2006).

The Chalk Group in most of the region has a relatively simple structure, although Allen et al. (1997) notes that minor faulting is a common feature and many small faults are thought to exist that, due to their small scale, are not described in this report. However in north Yorkshire, the Chalk Group is affected by the regionally significant North Craven–Vale of Pickering–Flamborough Head fault zone. There is no information in the literature consulted regarding the effect of faulting on the heads or groundwater flow in the Chalk in the depth range of interest, but Gale and Rutter (2006) suggests that faults may act as conduits for preferential flow.

The baseline chemistry of the Chalk of Lincolnshire has been studied by Smedley and Brewerton (1998) and that of the Chalk of Yorkshire and North Humberside by Smedley et al. (2004). Smedley et al. (2004) finds few data to assess the depth variation in groundwater chemistry and describes samples taken from above 100 m depth.

Smedley et al. (2004) reports that in Yorkshire and North Humberside, in low-lying near-coastal parts of the confined aquifer, the groundwater becomes increasingly saline as a result of mixing with sea-water. The age of the sea-water end member is unknown but sluggish groundwater movement in the region and combined trace-element and stable-isotopic evidence suggest that it is unlikely to be modern. Saline infiltration in the Holderness peninsula may have occurred at some point during the Holocene when sea level was higher than at the present day (Smedley et al., 2004). In addition, Elliot et al. (2001) describe saline intrusion in the Hull area. In the confined Chalk, the usable body of fresh groundwater is limited by the presence of saline waters. Historical over-abstraction of groundwater in the Hull area has induced the saline water interface to move westwards and northwards. Elliot et al. (2001) states that waters encountered in the Yorkshire Chalk aquifer are identified as complex (and potentially dynamic) mixtures between recent recharge waters, modern seawater and ancient seawater that entered the aquifer many millennia ago. The groundwater chemistry of the Chalk aquifer in Lincolnshire is broadly similar to that in Yorkshire and North Humberside. There is little evidence of ancient palaeowater in the Lincolnshire Chalk but the oldest, most immobile groundwater appears to be in the near-coastal belt of south Lincolnshire (Somercotes to Skegness) where salinity is high, 1970s tritium concentrations are low, ^{14}C shows the lowest per cent modern carbon and flow modelling suggests negligible groundwater movement (Smedley and Brewerton, 1998).

The Chalk in the depth range of active groundwater abstraction is highly permeable due to solutionally enlarged fracture porosity (Allen et al., 1997). However, there is no information regarding the permeability of the Chalk in the depth range of interest.

Early Cretaceous rocks

The Hunstanton, Carstone and Spilsby Sandstone formations are considered to form part of the Chalk aquifer system by Whitehead and Lawrence (2006), although hydraulic connections are spatially variable. The Hunstanton Formation, where present, directly underlies the Chalk Group. No information was found regarding the hydrogeology of these formations within the depth range of interest in the references cited.

The Hunstanton Formation is thin and possibly only constitutes a useful aquifer when it is in hydraulic continuity with the overlying Chalk Group. The Carstone Formation is unlikely to constitute an important aquifer in this region. The Carstone Formation is inferred to be in hydraulic continuity with the overlying Hunstanton Formation, and thus the Chalk Group, by Jones et al. (2000). Allen et al. (1997) reports that minor faulting at the base of the Chalk Group into the Carstone Formation can provide hydraulic continuity between the two. Similarly, in areas where the Carstone Formation lies directly above the Spilsby Sandstone Formation, the two units may be in hydraulic continuity. Jones et al. (2000) reports that north of the Caistor Monocline, the Tealby Formation is absent and the Spilsby Sandstone Formation may be in hydraulic continuity with the Carstone Formation (George, 1979).

The Spilsby Sandstone Formation is locally important for water supply in Lincolnshire. It rests unconformably on the predominantly low permeability Kimmeridge Clay Formation and is overlain by the Claxby Ironstone Formation and the confining clays of the Tealby Formation (Jones et al., 2000). Groundwater flow approximately follows the dip (which is broadly eastward) (Jones et al., 2000). The Speeton Clay Formation consists predominantly of fine-grained lithologies (mudstone, claystone) that are likely to have low permeability. Jones et al. (2000) describes the Tealby Limestone Member as a relatively minor aquifer. It has been reported as having a low yield, and containing water of poor quality, indicating long residence times and poor aquifer characteristics (Jones et al., 2000). No information has been found in the references cited regarding either the Spilsby Sandstone or the Speeton Clay formations within the depth of interest.

Mid and Late Jurassic sedimentary rocks

The Mid to Late Jurassic sedimentary rocks consist of a wide range of lithologies with widely varying hydrogeological characteristics. The Ampthill Clay and Oxford Clay formations of the Ancholme Group can be characterised as aquitards, while members of the Kimmeridge Clay and Kellaways formations, also in the Ancholme Group, can be described as locally important aquifers. Part of the West Walton Formation is designated as a principal aquifer. The Corallian, Ravenscar, Great Oolite and Inferior Oolite groups are all considered to be regionally important aquifers in the depth interval of active groundwater exploitation, and almost all the hydrogeological information for these units relates to them.

In the Ancholme Group, Gaunt et al., (1992) notes that the Elsham Sandstone Member of the Kimmeridge Clay Formation is locally in hydraulic contact with the Chalk Group and the Carstone Formation. It is utilised locally in South Humberside and further east it forms a thin, confined water-bearing unit, containing good quality sodium bicarbonate-type water (Berridge and Pattison, 1994). The Ampthill Clay and Oxford Clay formations are considered to form aquitards (Jones et al., 2000). In north Yorkshire, the Ampthill Clay and West Walton formations pass laterally into the coeval Corallian Group limestones. The Brantingham Member of the West Walton Formation is limited to the north of the Humber, and the lateral variations in both lithology and thickness mean that it is not a regionally significant aquifer. Gaunt et al. (1992) reports that the Brantingham Member is faulted against, and is likely to be in hydraulic contact with, the Kellaways Formation and the Lincolnshire Limestone, to the north-east of Brough. No evidence regarding the hydrogeological aspects of this group in this region in the depth range of interest has been identified from the references reviewed.

The Corallian Group forms a locally important groundwater source in north Yorkshire in the depth interval of groundwater exploitation and is also present in the region within the depth range of interest over the south-eastern part of its subcrop. Several large east–west trending faults traverse the Cleveland basin, separating the North York Moors from the Howardian Hills and Yorkshire Wolds. The downfaulted section is defined largely by the Vale of Pickering and the Helmsley and Filey faults (described in Northern area) to the north of the Vale of Pickering Syncline. These act as a hydrogeological boundary throwing the Kimmeridge Clay Formation to the south against Corallian limestones to the north (Allen et al., 1997). The group is overlain by the Ampthill Clay and Kimmeridge Clay formations, and is underlain by the Oxford Clay Formation, all of which are of low permeability (Allen et al., 1997). Recharge to the Corallian Group occurs both by direct rainfall recharge at outcrop and via surface water run-off or river flow into swallow holes (Allen et al., 1997). As with many other units in the region, almost all the hydrogeological information for the Corallian is related to the relatively shallow groundwater system, which is currently exploited for groundwater resources. Most of the flow through the actively exploited aquifer occurs along solution-enhanced fractures (Allen et al., 1997). However, it is not known if such features are present in the depth range of interest. Bearcock et al. (2015) described the groundwater chemistry in the Corallian Group aquifer of the Vale of Pickering, including available information on spatial and temporal variability. The sample locations are all either on, or very close to, outcrop and thus above the depth range of interest. There were no available data on groundwater chemical variations with depth.

In the literature cited there is no information on the hydrogeology of the Blisworth Limestone Formation of the Great Oolite Group in the depth range of interest.

The Inferior Oolite Group is present across much of Lincolnshire and just north of the Humber, and includes the Lincolnshire Limestone Formation, a regionally important aquifer (a principal aquifer). There is no information on the hydrogeology of the Inferior Oolite Group in the depth range of interest in the references cited. The Lincolnshire Limestone is a hard, fractured, carbonate aquifer. In the depth interval of currently exploited groundwater, groundwater movement occurs almost exclusively via fracture flow (Griffiths et al., 2006). The general direction of groundwater flow is downdip. Further east, where the aquifer is confined by the Mid Jurassic clays, it becomes increasingly artesian in nature (Griffiths et al., 2006).

Flow velocities of many hundreds of metres per day have been measured from tracer tests in the unconfined Lincolnshire Limestone Formation (Allen et al., 1997) and seasonal variations in water level can be large due to the importance of fracture flow and hence rapid response to recharge (Allen et al., 1997). However, it has been inferred from the high sustained yields that are obtained that the fracture system is extensive in the depth interval of currently exploited groundwater and that the principal fractures are connected to smaller systems, fed by slow seepage by intergranular flow (Allen et al., 1997). The Lincolnshire Limestone is locally in hydraulic continuity with the underlying Northampton Sand Formation, and boreholes into the

Lincolnshire Limestone Formation commonly extend through both aquifers (Griffiths et al., 2006). There may also be limited flow between the Lincolnshire Limestone Formation and the stratigraphically higher Blisworth Limestone Formation (a principal aquifer) through the Rutland Formation, but this is unlikely to be significant in terms of the overall aquifer resources (Allen et al., 1997). A review of the baseline groundwater chemistry of the Lincolnshire Limestone Formation was undertaken by Griffiths et al. (2006) but does not include any observations relevant to the depth range of interest.

Allen et al. (1997) and Jones et al. (2000) classify all five formations of the Ravenscar Group as minor aquifers based on their characteristics in the depth of active groundwater exploitation interval. However, there is no information regarding the hydrogeological properties of this group in the depth range of interest in the references cited.

Lias Group

There is very little hydrogeological information on the hydrogeology of the Lias Group in the reviewed literature and what is available is only for the depth interval currently exploited for groundwater resources. The bulk of the formation comprises low permeability mudstones. However, at outcrop more permeable horizons in the Lias Group may yield limited groundwater supplies across the region. North of the Market Weighton high (Cleveland basin) Jones et al. (2000) notes that thin limestone bands in the Calcareous Shale Member of the Redcar Mudstone Formation contain some water, however, the few recorded transmissivities are low (Jones et al., 2000). Similarly, Jones et al. (2000) reports low transmissivities in formations south of the Market Weighton high (East Midlands shelf). No additional evidence regarding the hydrogeological aspects of this unit in this region has been identified from the references reviewed.

Triassic Penarth Group

The Institute of Geological Sciences (1980) states that the Penarth Group in East Yorkshire consists of low permeability marls, limestones and black shales. No further evidence regarding the hydrogeological aspects of this unit in this region has been identified from the references reviewed.

6.3.2 Hydrogeology of the regionally confining Mercia Mudstone Group

The Mercia Mudstone Group is a continuous, mudstone-dominated succession that regionally confines the units that it overlies and so is treated here as one of the four hydrogeologically distinct hydrogeological units of the region. Generally the Mercia Mudstone Group is regarded as a relatively low permeability unit that confines the underlying Sherwood Sandstone Group (Jones et al., 2000). Although effectively not forming an aquifer in many areas, limited quantities of groundwater are occasionally obtained from the Mercia Mudstone Group (Jones et al., 2000). These more permeable parts of the group comprise ‘skerries’ and the more arenaceous Tarporley Siltstone and Arden Sandstone formations. The limited hydrogeological information on the skerries and the Tarporley Siltstone and Arden Sandstone formations is only available for the depth interval where groundwater is actively exploited, and is not available for the depth range of interest. The skerries are occasional thin, impersistent, dolomitic siltstones and sandstones within the Mercia Mudstone Group, and may contain and transmit limited quantities of groundwater through fractures. Skerries are present, to a varying degree, throughout most of the mudstone sequence except the uppermost Blue Anchor Formation (Jones et al., 2000). Thicker sandstone horizons are present in the Arden Sandstone Formation and in the basal part of the sequence (the Tarporley Siltstone Formation); the two formations are not considered PRTIs. There is no information regarding the hydrogeological properties of these formations in the references reviewed for the region. However, the Tarporley Siltstone Formation is sometimes in hydraulic continuity with the underlying Sherwood Sandstone Group (Jones et al., 2000). No evidence regarding the hydrogeological aspects of the Esk Halite/Röt Halite Member of the Mercia Mudstone Group in this region has been identified from the references cited.

6.3.3 Hydrogeology of the younger sedimentary cover below the Mercia Mudstone Group and above the Carboniferous

The cover sequence below the confining Mercia Mudstone Group consists of the Triassic Sherwood Sandstone Group, a nationally important aquifer, where it is actively exploited near the land surface, and the underlying, hydrogeologically variable Permian Zechstein and Rotliegendes groups.

The hydrogeological characteristics of this groundwater system are a function of the overall geometry of the sedimentary sequence, the confining nature of the overlying Mercia Mudstone Group, and the outcrop and nature of individual units within the groundwater system. The Sherwood Sandstone Group sedimentary rocks crop out in the west of the area, and, as with other cover sedimentary rocks in the region, broadly dip to the east. They become increasingly confined eastwards beneath the thick, overlying Mercia Mudstone Group. Primarily as a consequence of increasing confinement and overburden, the hydrogeological characteristics and the hydrochemistry of the groundwater in this system change progressively from west to east.

Edmunds and Smedley (2000) studies residence time indicators in the Sherwood Sandstone Group of the East Midlands. They sampled from Gainsborough in the north to Newark in the south, and from Worksop in the west to Welton in the east: the study area thus falls partly within this region and partly within the adjacent Pennines region. The age of the fresh water is shown to be up to 100 ka (Edmunds and Smedley, 2000). There is a marked change in salinity down gradient with saline waters sampled at Welton. The saline waters have an extrapolated age in excess of 1 Ma, although unlike the main flow line where continuous evolution of the hydrochemistry has taken place, there may be a hiatus between the main group of fresher groundwaters and the deeper saline waters (Edmunds and Smedley, 2000).

Separation/rapid flow from depth

Neither the Permian Zechstein Group nor the Rotliegendes Group, the other units in the groundwater system below the Mercia Mudstone Group, crop out in the study area and hence neither receive direct recharge within the study area, although both groups are at least in part in the depth range of interest over the region.

6.3.4 Hydrogeology of the Sherwood Sandstone Group

In the depth interval of active groundwater exploitation, the Sherwood Sandstone Group forms a principal aquifer in the north-east of England, providing water resources for public supply, agriculture and industry (Allen et al., 1997). Across much of the region it is confined downdip by the Mercia Mudstone Group within the depth range of interest, however, it is utilised as an aquifer at depths of over 400 m in the Gainsborough area. Even where exposed in the north-west of the region, superficial deposits, can confine the aquifer and cause local artesian heads in the sandstones (Institute of Geological Sciences, 1982; Allen et al., 1997). Although regionally confined by the Mercia Mudstone Group, locally some leakage between the sandstones and overlying strata has been documented (Allen et al., 1997; Smedley and Brewerton, 1997). Over most of the region, the Sherwood Sandstone Group overlies the Roxby Formation (of the Permian Zechstein Group). It is considered to form the relatively low permeability base to the sandstone aquifer (Allen et al., 1997).

In the depth interval of active groundwater exploitation, the Sherwood Sandstone Group stores and transmits water by both intergranular and fracture flow, however, the dominant mode of flow in the depth range of interest in the confined Sherwood Sandstone Group is uncertain. Groundwater flow is typically conceptualised as reducing rapidly with depth in the unconfined aquifer. For example, flow logs have been interpreted as showing that there is little flow contribution from beneath 120 m (Allen et al., 1997). Allen et al. (1997) also notes that the confined aquifer has a generally low transmissivity. This can be attributed to intergranular flow, with all the fractures having been closed by the overburden pressure of 200 m of Mercia Mudstone Group strata (Allen et al., 1997). Hydrogeochemical evidence also generally indicates a reduction in groundwater circulation with overburden in the sandstones. For example, Allen et al. (1997) notes there is apparently less water circulation with depth (as indicated by poor quality water at depth), and the Institute of Geological Sciences (1982) reports that several boreholes at Selby (just west of this region) have been abandoned due to the unacceptably high salinity of the groundwater, which is attributed to an upward seepage of saline water from the underlying Permian strata. The effects of faulting on flow and heads in the depth interval of active groundwater exploitation have been documented by Allen et al. (1997), which notes that, although faults are present throughout the Permo-Triassic sandstones and that they may be important locally, their hydraulic effects are not necessarily important on a regional scale. The effect of faulting in the confined sandstones in the depth range of interest is uncertain.

6.3.5 Hydrogeology of the Zechstein Group and the Rotliegendes Group

The Zechstein Group is hydraulically very variable, reflecting the variety of lithologies within the group in the region. There is only limited information regarding the hydraulic properties of the group in the depth range of interest. At relatively shallow levels in the depth interval of active groundwater exploitation, Allen et al. (1997) characterises the Roxby Formation (formerly known as the Upper Permian Marl) as an aquitard, while the underlying dolomitic limestones form regionally important aquifers. The Sneaton Halite Formation is present in the depth range of interest in part of the region (See Section 3.2.7 and Table 3), but no evidence regarding the hydrogeological aspects of this unit has been identified from the references reviewed.

The available information on the hydrogeology of the dolomitic limestones of the Zechstein Group is principally derived from areas at outcrop or close to outcrop, e.g. Allen et al. (1997), and as they do not crop out in the region there is only limited information regarding the hydraulic properties of the aquifer units in the depth range of interest. Typically, the hydrogeology of these aquifers is controlled by lithology and structure. Variations in lithology result in changes in hydraulic conductivity and hence transmissivity and yield. However, the greatest control on the aquifer properties is the extent of the fracturing. As a consequence, aquifer properties are extremely unpredictable (Allen et al., 1997). Although uncertain, fracturing and structure of the limestones at depth are expected to influence regional trends in the permeability of this unit. In areas of active groundwater exploitation in adjacent regions, the Edlington Formation (mid Permian Marls) functions as a 'leaky' aquitard and thus generally maintains a slight head difference between the formations above and below it (Allen et al., 1997). By inference, small head differences may also be maintained between these formations in the depth range of interest.

There is only limited hydrogeochemical information on the Zechstein Group limestones in the depth range of interest. In adjacent regions, in areas of active groundwater exploitation, the chemistry of the groundwaters is predominantly affected by the dissolution of dolomite (Brewerton and Edmunds, 1997). Brewerton and Edmunds (1997) also notes that at depth the groundwater becomes saline.

There is very limited information regarding the hydraulic properties and characteristics of the Rotliegendes Group (Basal Permian Sands Formation) in the depth range of interest. Although at relatively shallow depths, relatively high intergranular permeability has been inferred (Downing and Grey, 1986), even at shallow depths the effective aquifer may be reduced further by cementation. Near the coast at Cleethorpes, where the Rotliegendes Group is considerably below the depth range of interest, a geothermal exploration well found only 8.5 m of suitable reservoir rock out of 26 m of sandstones and conglomerates and low permeability (Downing and Grey, 1986). Poor quality water at depth is exemplified by the analysis of waters from the Basal Permian Sands Formation from an upward-drilled borehole from the Carboniferous strata at Horden, quoted by Edmunds (1975), where the total mineralisation is 58 000 mg/L (Brewerton and Edmunds, 1997Horden is approximately 11 km north-west of Hartlepool, near Peterlee, and outside the Eastern England region.

6.3.6 Hydrogeology of the Carboniferous (older sedimentary rocks) and basement rocks

The deep groundwater system consists of confined basement rocks and igneous intrusions and older, Carboniferous, sedimentary cover, which can be characterised (directly and by analogy) as consisting of relatively immobile, old and highly mineralised and saline groundwater within relatively low permeability units.

Based on the references reviewed, there is no direct evidence regarding the hydrogeological characteristics of the Carboniferous strata in the region. Downing and Howitt (1969) studied the chemistry of deep groundwater in the Carboniferous rocks of the East Midlands (south-west of the Eastern England region). Values of total concentration of groundwaters in the Carboniferous Limestone Supergroup are found to be in excess of 90 000 mg/L north-east of Gainsborough. It is postulated that the saline groundwaters now found in the Carboniferous rocks are probably of Carboniferous origin over most of the East Midlands (Downing and Howitt, 1969) indicating absence of significant regional groundwater circulation in this unit.

Based on the references reviewed, there is no evidence regarding the hydrogeological characteristics of the Ordovician igneous rocks or intrusive igneous rocks (Wash batholith) in this region.

6.4 EVIDENCE FOR CONNECTIONS BETWEEN GROUNDWATER SYSTEMS

6.4.1 Geological pathways

There is no evidence in the reviewed literature for relatively rapid subvertical flows from the depth range of interest to the current land surface and there are no known thermal springs ($\geq 15^{o}$C) in the region.

Over a range of scales, faults within the region may act to compartmentalise groundwater by reducing flow across the structures, while in other cases they may act to enable enhanced flow of groundwater and may be associated with localising flows from depth to surface springs. Major faults in the region are described in Section 5.3. In addition, faults may disrupt or enhance local groundwater flow by juxtaposing more or less permeable units either side of fault strands and may localise flow to springs.

6.4.2 Anthropogenic pathways

There are a number of deep boreholes in this region. If not fully sealed these could form pathways for vertical flows between deeper and relatively shallow groundwater systems that would otherwise be hydraulically separated by intervening confining units such as the Mercia Mudstone Group. This would only happen if there were upward heads. Many areas with more than one borehole over 200 m deep (below NGS datum) have been identified in this region (see Screening topic 5). These are mainly located in the north-east of the region and the west of the region where the highest intensity of drilling, around 10 to 15 boreholes per square kilometre, is related to oil and gas exploration and exploitation around Gainsborough. The grid square with the highest recorded density of deep boreholes is TF0376 (Sudbrooke), which has a count of 45. Many hydrocarbon wells penetrate to greater than 1000 m. In addition, there are metal mines over 100 m deep (two areas in the Cleveland Ironstone orefield), coal mining over 100 m deep (two areas on the western margin of the region), and evaporite mining over 100 m deep (Boulby Mine: 1000 to 1200 m deep; potash and halite). The Environment Agency are currently undertaking studies to investigate how recharge could be impacted by the many deep investigation boreholes in the Teeside area, and how natural hydrogeology has been impacted by historical and current anthropogenic activities (such as brine winning). Preliminary findings have been interpreted as showing that the piezometric heads in the underlying Zechstein Group limestones have driven brine from in situ to the surface through the overlying Sherwood Sandstone Group aquifer, and that this is evidence of the existence of artificial groundwater flow paths and hydraulic gradients at depths up to the upper parts of the Zechstein Group limestones. In addition, monitoring of ongoing dewatering activities at an anhydrite mine near Billingham into the River Tees (in the adjacent Northern England region) have been interpreted as showing potential hydraulic connections both with the underlying Zechstein Group and the overlying Sherwood Sandstone Group.

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 Eastern 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 Eastern 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 19; RWM 2016b; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next one million years is open to conjecture (Loutre and Berger, 2000). This is because the impacts of global warming and the current melting of the Greenland Ice Sheet on the long-term climate system are poorly understood, although the general scientific consensus is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions means that their occurrence cannot be discounted.

Glaciers are important geological agents because they are highly effective at eroding and redistributing surface materials. Indeed, the landscape of much of Northern Ireland, Wales and northern and central England represents a legacy of past glaciation. Within the context of this report, glaciers can affect the subsurface within the depth range of interest by a variety of different mechanisms (RWM, 2016b).

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

7.2.2 A regional perspective

Based on geological evidence it is widely accepted that Eastern England has been glaciated during several lowland and continental-scale glaciations during the past two and a half million years (Quaternary Period; Shaw et al., 2012; Clark et al., 2004). During the Late Devensian glaciation (about 29 000 to 15 000 years ago), the region was inundated by glaciers emanating from several highland areas of northern Britain (Clark et al., 2012). This glaciation extended over much of northern and central UK and was the second of two known continental-scale glaciations to affect the UK (Clark et al., 2004). Direct evidence for earlier glaciations in Eastern England is preserved locally although the timing of these events remains equivocal. However, the position of Eastern England relative to other ice accumulation areas in northern Britain made it highly susceptible to being glaciated (RWM, 2016b).

Over the next million years, assuming Britain is glaciated, it is likely that Eastern England will experience lowland and continental-scale glaciation (RWM, 2016b). This is because of its proximity to other ice sources in northern Britain such as the Lake District, the Pennines and Scotland (RWM, 2016b). The formation of meltwater-incised valleys beneath glaciers (tunnel valleys) in lowland areas of Eastern England adjacent to the margins of larger-scale lowland and continental glaciations may result in the localised lowering of the ground surface towards the top of the depth range of interest (RWM, 2016b). The formation of tunnel valleys can lead to the development of highly localised groundwater behaviour and chemistry (RWM, 2016b). The region may also be affected by isostatic rebound and/or a glacier forebulge during a lowland or continental glaciation affecting an adjacent onshore and/or offshore region such as northern England and the North Sea (RWM, 2016b). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (RWM, 2016b). The extensive coastline of Eastern England makes coastal areas of the region susceptible to saline groundwater incursion due either to global sea-level change (driven by global patterns of glaciation) or regional isostasy (RWM, 2016b). Saline groundwater incursion may alter the temporal and spatial patterns of groundwater behaviour (French, 2007).

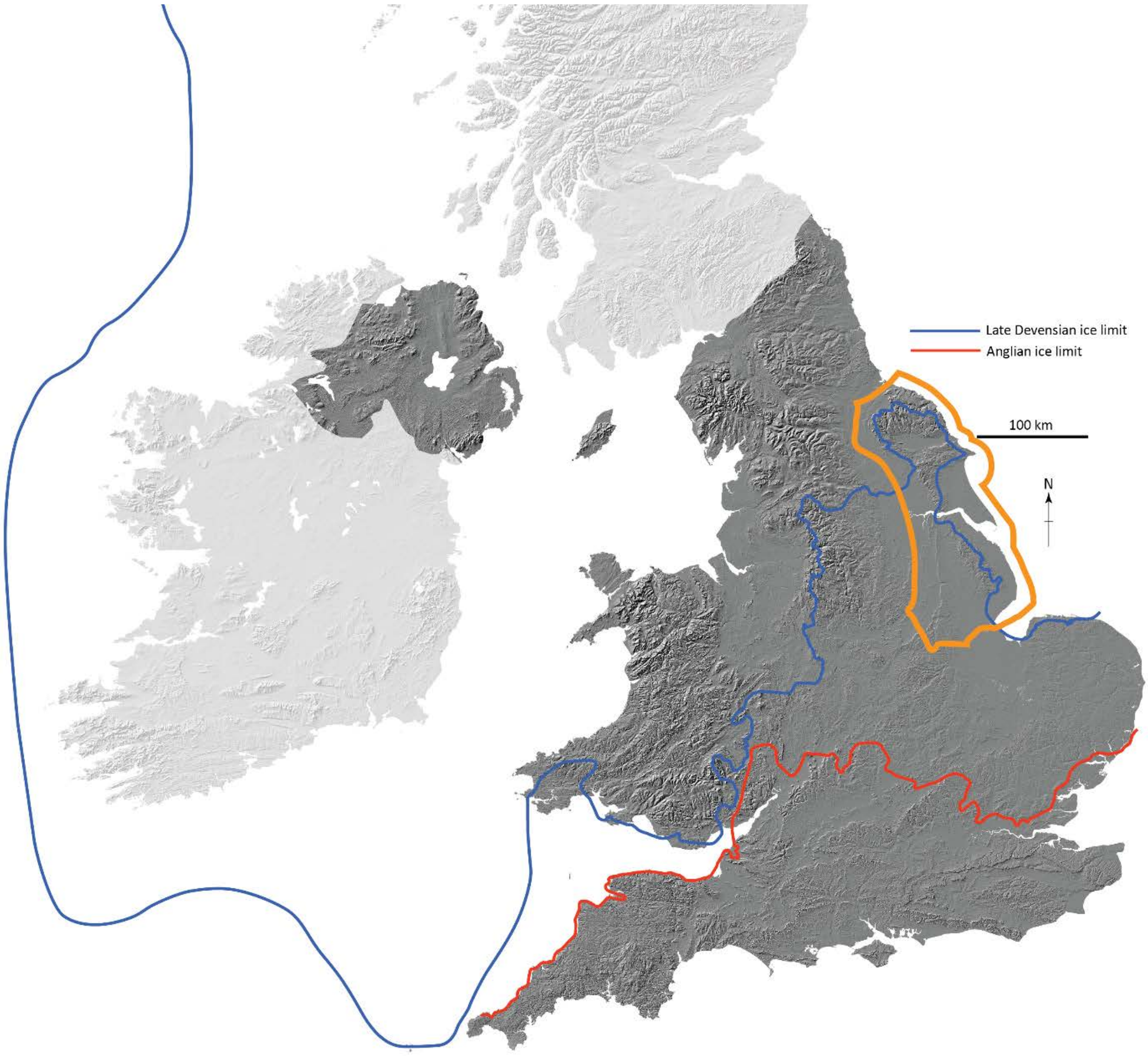

Figure 19 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and Late Devensian (around 30 to 16 ka). The location of the Eastern England region is delineated by the orange line. Produced using Copernicus data and information funded by the European Union – EU-DEM layers © EEA.

7.3 PERMAFROST

7.3.1 A UK-scale context

Permafrost (frozen ground) occurs when the temperature of the ground remains below 0°C for at least two consecutive years (French, 2007). Permafrost, therefore, develops where average air temperatures are much colder than the present day and consequently there is potential for significant thicknesses of permafrost to develop over decadal to centennial timescales (Busby et al., 2014). It is also important to note that permafrost and glaciation are not synonymous. Whilst many glaciated areas are subjected to periglacial processes, not all areas affected by permafrost will become glaciated. For example, areas situated to the south of the major limits of glaciation in the UK (see Figure 19) 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 Eastern England will be subjected to the development of permafrost to a depth of a few hundred metres (Shaw et al., 2012; Busby et al., 2014). The development of permafrost can affect groundwater chemistry and behaviour (Busby et al., 2014).

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 20). 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 20). 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).

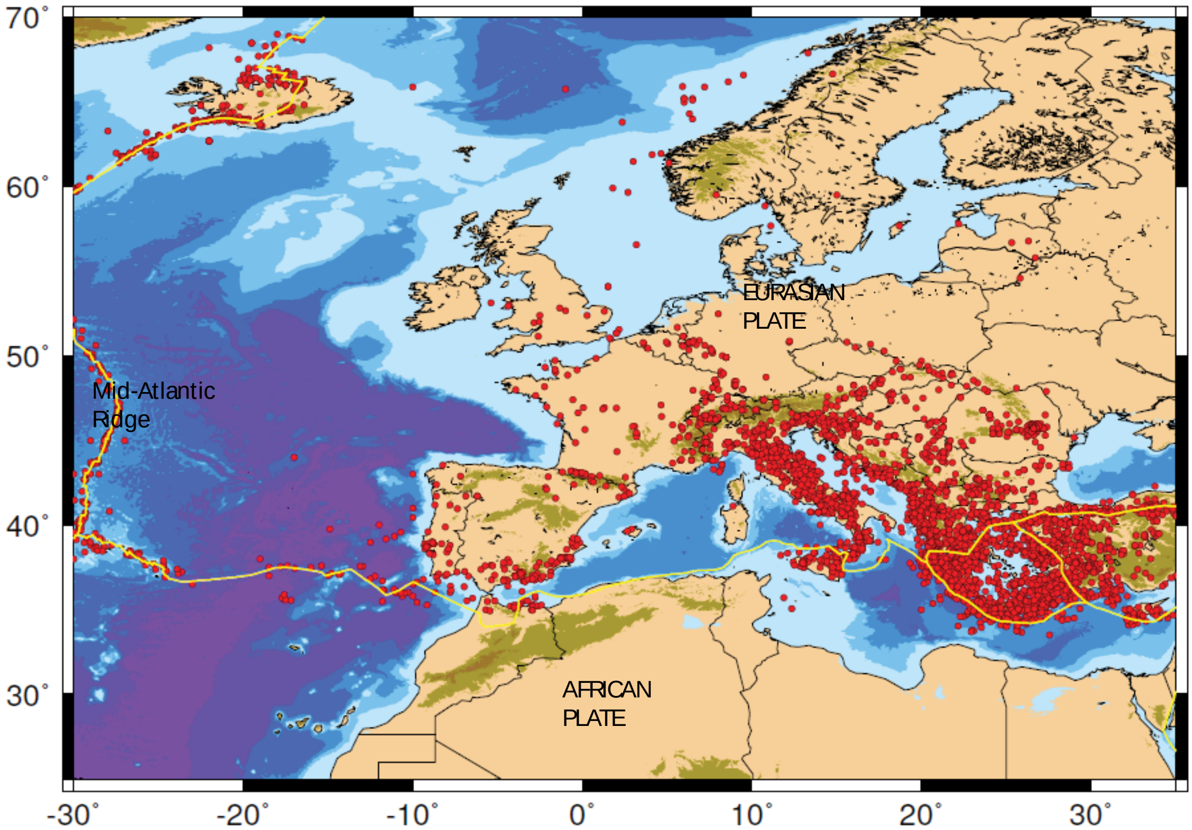

Figure 20 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated 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 main shocks only. In the UK, the number of dependent events of significant magnitude (i.e. > Mw 3) is so small that it is easy and unambiguous to identify them by hand, which obviates the need to apply algorithmic methods.

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

A requirement for any statistical analysis of seismicity is that one needs to know the extent to which the record of main shocks in an earthquake catalogue is complete. For example, some historic earthquakes that happened may not be present in the catalogue because no record of them survives to the present day. Normally, completeness improves with time (better nearer the present day) and also with magnitude (better for larger earthquakes). Thus one can describe a series of time intervals within which it is considered that the catalogue definitely contains all earthquakes above a certain magnitude threshold. This threshold value can be defined as the lowest magnitude at which 100 per cent of the earthquakes in a space-time volume are detected (Rydelek and Sacks, 1989). Therefore it is usually low for recent seismicity and gets progressively higher back in time. For this study we use the completeness estimates for the UK catalogue determined by Musson and Sargeant (2007), which are shown in Table 1. 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 21 shows a map of all of the mains 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 21).

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 21), 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 approximately 20 km (Turbitt et al., 1985). The event was followed by a prolonged number of after shocks including a Mw 4.0 event on 18 August 1984. There is evidence that earthquakes with magnitudes of Mw 5.0 or greater in this part of North Wales occur at regular intervals of about 150 years. For example, events similar to the 1984 earthquake occurred in 9 November 1854 (Mw 5.0), 7 October 1690, and probably July 1534 (Musson, 2007).

7.4.3 Earthquake depths

No earthquake in the UK recorded either historically or instrumentally is known to have produced a surface rupture. Typical fault dimensions for the largest recorded British earthquakes are of the order of 1 to 2 km. Therefore, it is difficult to accurately associate earthquakes with specific faults, particularly at depth, where the fault distributions and orientations are unclear and because of the uncertainties associated with depth estimates. The uncertainties in the focal depths determined for earthquakes are generally large, up to a standard deviation of ±10 km. Figure 22 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 22).

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

7.4.4 Maximum magnitude

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

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

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

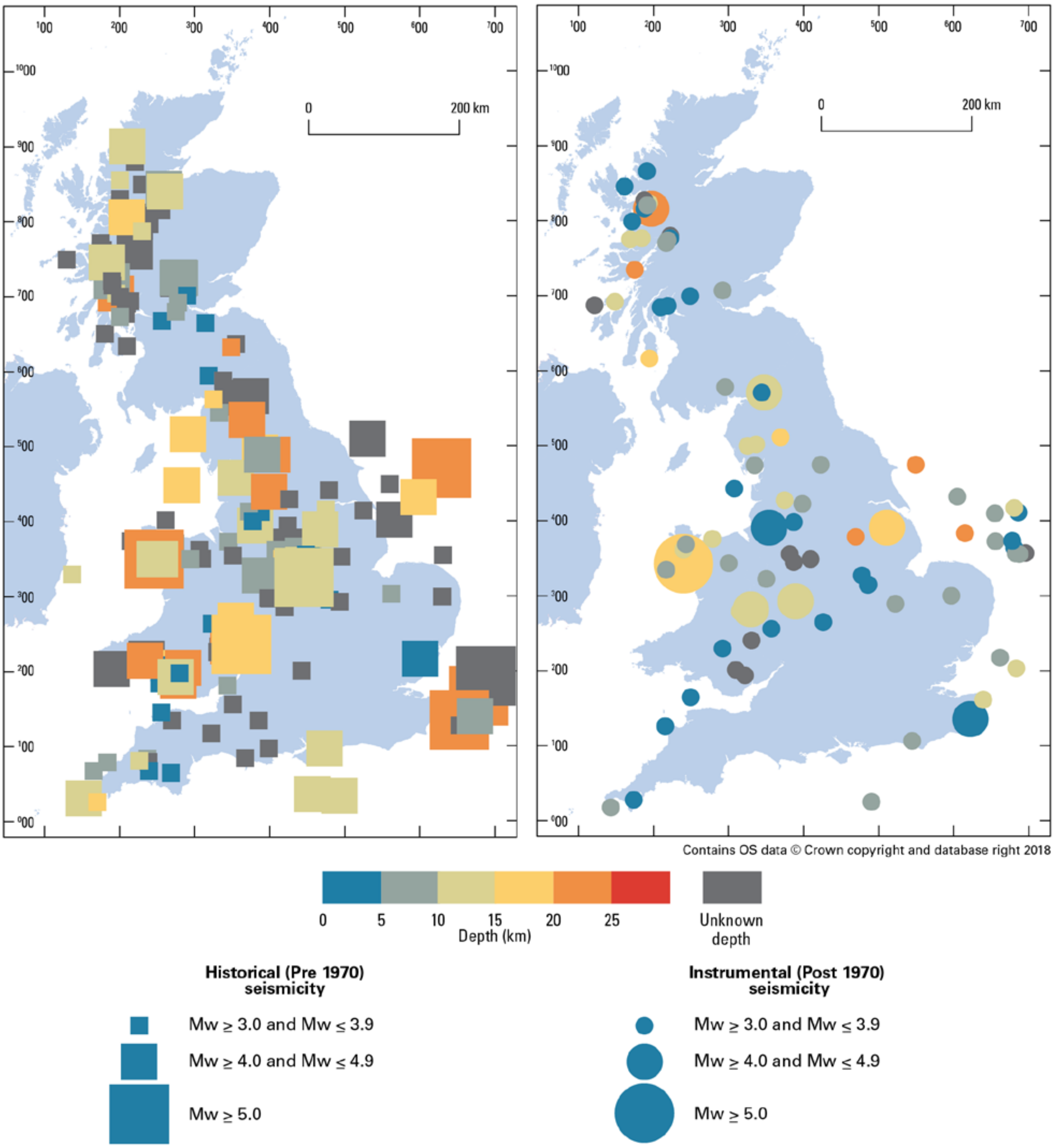

Figure 21 Distribution of the mains shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake-free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

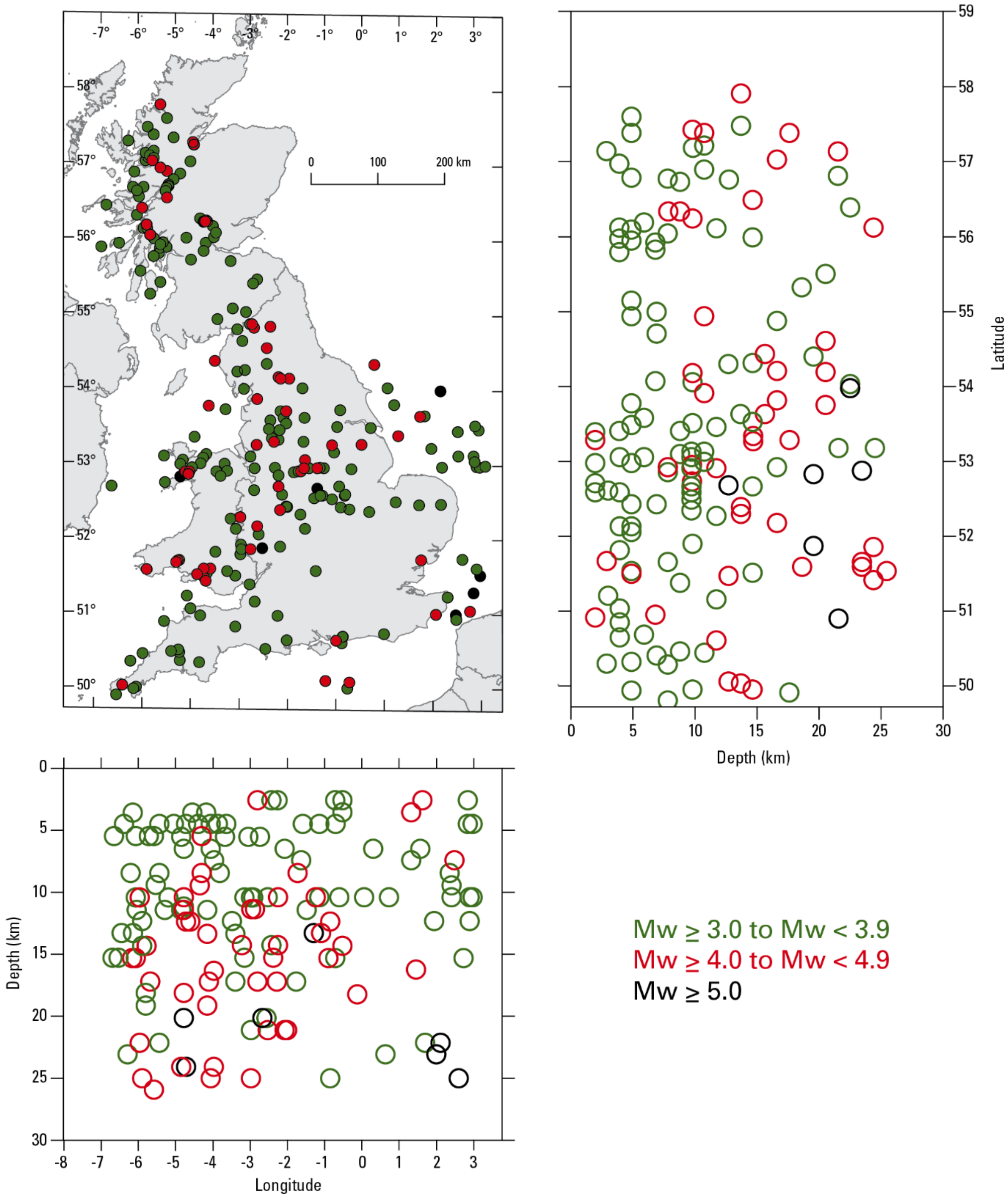

Figure 22 Relationship between the focal depth and the geographical distribution of the mains hocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake-free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

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) argue that these are restricted to metre-scale vertical movements along pre-existing faults.

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

7.4.7 Conclusions

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

There are two crucial limitations in studies of British seismicity:

- The duration of the earthquake catalogue (approximately 700 years) is very short compared to the recurrence interval of large earthquakes in intraplate areas (thousands of years) and geological processes (millions of years). As a result, our understanding of earthquakes and earthquake generating processes is incomplete.

- The lack of surface ruptures does not allow us to associate seismic activity that has occurred with specific tectonic structures.

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

7.4.8 A regional perspective

Figure 23 shows earthquake activity in the Eastern England region. This is a region of relatively low seismicity. The largest earthquake in the catalogue had a magnitude of Mw 4.9 and occurred near Market Rasen on 29 February 2008 (Ottemöller and Sargeant, 2010). This earthquake was felt widely across the British Isles and caused some superficial damage near the epicentre. The deep focus for this earthquake (18 km) may have been the reason that the damage caused by the earthquake was relatively slight for an event of this size.

Slightly more earthquakes have been observed in the area immediately offshore. These include the magnitude Mw 5.9 Dogger Bank earthquake, which occurred in 1931. This is the largest recorded earthquake in Britain for which a magnitude can be reliably determined (Musson, 1994). The epicentre was in the Dogger Bank area, around 120 km north-east of Great Yarmouth. It was felt all over Britain and the east of Ireland, north of France, Belgium, the Netherland, Denmark and south-west Norway. Damage was reported along the east coast of England, mainly to chimneys and plaster (Neilson et al., 1986; Musson, 1994).

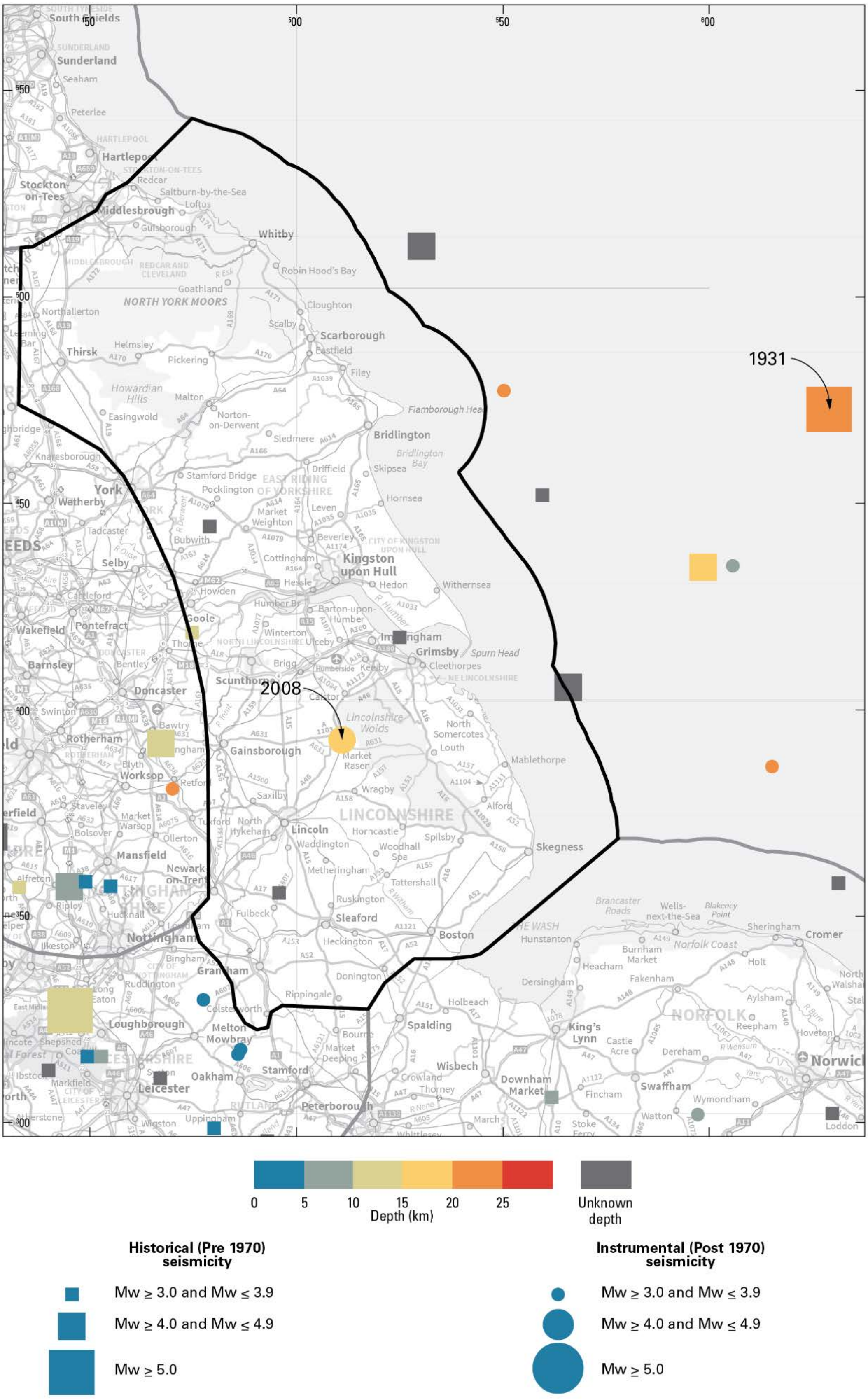

Figure 23 Historical and instrumentally recorded earthquakes in the Eastern England region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © 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 Eastern 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 REGION

The distribution of mineral resources in the Eastern England region is shown in Figure 24. Potash is mined at depth in the north-east of the Eastern England region and an area near Whitby has recently received planning approval for the development of a deep polyhalite mine. Bedded iron ores have been mined at depth in Cleveland and at shallow depths elsewhere in the region. There are extensive resources of deep and very deep coal over much of the region but these have only been exploited in the north-west. There are several small onshore oil and gas fields and the region is prospective for shale gas. One of the Southern North Sea gas fields lies about 26 km offshore. Salt caverns have been developed in north Yorkshire for gas storage.

8.3 COAL AND RELATED COMMODITIES

The distribution of coal resources in the Eastern England region is shown in Figure 26. There are deep (up to 1 km in depth) and very deep (over 1 km in depth) coal resources underlying most of the region. These extend from its southern edge as far north as Malton. Deep coal also extends offshore along the coast of North Yorkshire and far out into the Southern North Sea. On account of its depth in this region, coal has only been exploited in a small area near Selby. Following the closure of the Selby complex of mines in 2004, no deep mines are now working. Deep coal mining was proposed around the Nottinghamshire/Lincolnshire border near Witham, but the licence was subsequently withdrawn.

There are no current licences for coalbed methane, coal mine methane, abandoned mine methane or coal gasification. However petroleum exploration and development licences (PEDL) have been granted around York, Pocklington, Goole, Scunthorpe, Lincoln and Worksop for which there is no further information available in the public domain.

8.4 POTASH, HALITE, GYPSUM AND POLYHALITE DEPOSITS

Permian potash deposits occur in the north-east of the region, both onshore and offshore. Potash underlies an extensive area around Whitby and from Scarborough to Hornsea. All resources are contained within the Boulby Halite Formation, which dips gently to the east, as a result of which the workings deepen as they go beyond the coast. Onshore they are shallowest around the mine shaft at Boulby. Boulby potash is Britain's only source of the fertiliser raw material potash. Currently salt and potash are extracted but resources of polyhalite are also being investigated.

These deposits are mined at Boulby potash mine to depths up to 1350 m and the workings reach a distance of over eight kilometres offshore under the North Sea. Boulby potash mine, which has been operational since the 1960s, is currently investigating the potential to mine polyhalite from where it occurs beneath the potash bed currently exploited.

Also in the region, York Potash has recently been granted planning permission for a new mine to extract polyhalite deposits to the south-east of Whitby from depths up to about 1500 m.

The north-eastern part of this region is also underlain by considerable thicknesses of salt. This was formerly mined by brine wells located at the northernmost extremity of the region to the south of Middlesbrough. Brine pumping took place here for a considerable period, starting in 1876 and ending in 2002; the deepest extraction was from around 300 m. The salt continues offshore into the North Sea for a considerable distance.

Salt caverns have been developed in north-east Yorkshire for gas storage.

8.5 OTHER BEDDED AND MISCELLANEOUS COMMODITIES

There are bedded Jurassic iron ores in the Cleveland orefield (see Figure 24) that have been extensively worked from depths up to 200 m below NGS datum. Deep mining was concentrated around Upsall mine, north-west of Guisborough, and a cluster of mines including Skelton, Lingdale, Kilton and Liverton between Guisborough and Loftus. Underground workings were extensive, following the bedded ore, and cover some 40 km^2. Much of the ore in this area is now worked out. From 1875 to 1900 the Cleveland industry supplied half of all the iron ore produced in Britain. Originally the ironstone was extracted in quarries and small drifts along the outcrop. Subsequently shafts were sunk to extract the ironstone under increasing cover downdip. Total iron ore production from the orefield between 1854 and 1964, when the North Skelton mine closed, was some 372 million tonnes. The high cost of mining, the low grade of the ore and competition from high-grade, foreign iron ores progressively reduced the viability of the operations.

Similar iron ores have been mined in the Scunthorpe, Claxby, Caythorpe, Grantham and Melton Mowbray orefields but from depths shallower than 100 m below NGS datum.

Whinstone, a basic igneous rock, has been mined underground from the Cleveland Dyke but at depths less than 100 m below NGS datum. Jet has also been worked in the region by underground methods but at depths significantly less than 100 m below NGS datum.

8.6 VEIN-TYPE AND RELATED ORE DEPOSITS

There are no known vein-type and related ore deposits in the region.

8.7 HYDROCARBONS (OIL AND GAS)

There are a number of small conventional gas and oilfields onshore in the region. There are 24 known oilfields and 17 producing oilfields in northern and western Lincolnshire and eastern Nottinghamshire. Lincolnshire has been intensively explored for oil and gas since before the Second World War. This has led to many discovery wells and the development of a number of producing oilfields in the county. There is also gas production from Saltfleetby in east Lincolnshire, and it is thought likely that there will be further small oil and gas discoveries in these areas in the future.

In the north of the region, around the Vale of Pickering and the North York Moors, extensive areas have been licensed for gas exploration and there are producing wells at Kirkby Misperton, Malton, Ebberston Moor, Marishes and Pickering, as well as 11 known gas fields in the north and a further one around Saltfleetby in the south.

Some of the more westerly of the Southern North Sea gas fields are located about 26 km off the east coast of the region.

There are areas prospective for shale gas in the north of the region, in a large tract either side of the Vale of Pickering, extending from York to the coast, and a smaller area to the north-west of Lincoln. An exploration well has been drilled to investigate the potential for shale gas at Kirby Misperton.

8.8 GAS STORAGE

Eastern England hosts three differing underground gas storage environments: salt caverns, depleted hydrocarbon fields and hard rock caverns (without water curtain), with operational facilities in two and a planned/consented storage in the other.

An underground gas storage (UGS) facility was planned in the depleted Saltfleetby gas condensate field, in the east of the region, some 10 km east of Louth. The proposed storage facility gained planning consent in 2010 and would utilise the sandstone reservoirs of late Namurian and early Westphalian age at a minimum depth of 2240 m below NGS datum. Other depleted fields at shallower depths have been considered for UGS within the region and reached differing stages in the planning application process. These include the Welton and Gainsborough–Beckingham oilfields near Gainsborough, and the Caythorpe gas field, west of Bridlington in East Yorkshire. Caythorpe has gained consent, but to date, none have been converted to storage facilities, with Caythorpe awaiting a final investment decision.

Britain’s first offshore gas storage facility in the depleted Rough gas field lies about 27 km offshore from Spurn Head, just outside the 20 km zone being considered. The reservoir is within a sandstone in the (early Permian) Rotliegendes Group and the field was converted to Britain’s biggest gas storage facility in 1985.

Salt-cavern storage facilities have been constructed and are operational in the region, being hosted in the onshore areas of the large Permian (Zechstein Group) salt basin of the Southern North Sea. Two salt-cavern gas storage facilities are operational on the east coast of Yorkshire at Hornsea (Atwick) and Aldbrough (Phase I), and a number of former brine caverns are operational on Teesside. The Hornsea and Aldbrough storage facilities comprise a total of nine caverns each, constructed by solution mining in the Permian Z2 Fordon Evaporite Formation at a depth greater than 1700 m below NGS datum. Hornsea was the UK’s first specifically designed salt cavern storage facility, having commenced operation in 1979. A second Aldbrough storage facility (Phase II) was planned and consented, but development appears to have been shelved. Offshore, these halite beds thicken, but will be at depths greater than 1000 m.

In the extreme north of the region, extending into the south-eastern parts of the adjacent Northern England region, the Teesside salt field in south Durham, comprises thin salt beds of the (Middle or Main) Boulby Halite Formation (Permian age, Z3 cycle). These salt beds form the Billingham, Saltholme, Greatham and Wilton brine fields, from which brine has been won, with some of the former brine caverns having been converted for storage purposes. Products stored include various industrial wastes, gas, liquid petroleum gas (LPG) and hydrogen. The caverns are in the general depth range from 350 to 500 m below NGS datum, within the depth range of interest. Offshore, these halite beds deepen eastwards but are generally at depths of less than 1000 m.

In the mid 1980s, an underground LPG storage facility was constructed in the Chalk Group at Killingholme on the south bank of the Humber, North Lincolnshire, in the centre of the region. Two caverns were mined in the lower part of the Welton Chalk Formation (White Chalk Subgroup) with the sumps extending down into the top of the Ferriby Chalk Formation (Grey Chalk Subgroup) at a depth of about 200 m below NGS datum. The two caverns have a combined storage capacity of about 60 000 tonnes of LPG. The chalk, the base of which is at its deepest at about 200 to 250 m below NGS datum at Grimsby on the Lincolnshire coast and about 500 m below NGS datum south of Bridlington on the East Yorkshire coast, extends offshore into the Southern North Sea.

8.9 GEOTHERMAL ENERGY

The Eastern England region is underlain by thick sedimentary successions, including the Sherwood Sandstone Group brine aquifer and basal Permian sandstones. Regional mapping has inferred that, in the deeper areas, the basal Permian sandstones could reach up to 2200 m depth, and potentially exceed 60°C at its base.

The region was evaluated by the Department of Energy for its geothermal potential in the 1980s, with testing focused on the Sherwood Sandstone Group. In 1984 a borehole was drilled at Cleethorpes to a depth of 1900 m, where average geothermal gradients of 31.9°C per kilometre were confirmed, with temperature in the basal Permian sandstones of 64.5ºC. The Cleethorpes No. 1 Borehole was not developed further because of the low permeability of the sandstones. Although not nationally significant, the area has potential for local, low-enthalpy heating schemes.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are clusters of deep (greater than 200 m below NGS datum) boreholes in the region (see Figure 25). These have largely been drilled for the evaluation of potash and polyhalite resources in the north-east of the region, for the evaluation of coal resources in the west of the region and for oil and gas exploitation elsewhere. The highest intensity of drilling is related to oil and gas exploration and exploitation, with some of the highest values of about 10 to 15 boreholes/km^2 located near Gainsborough.

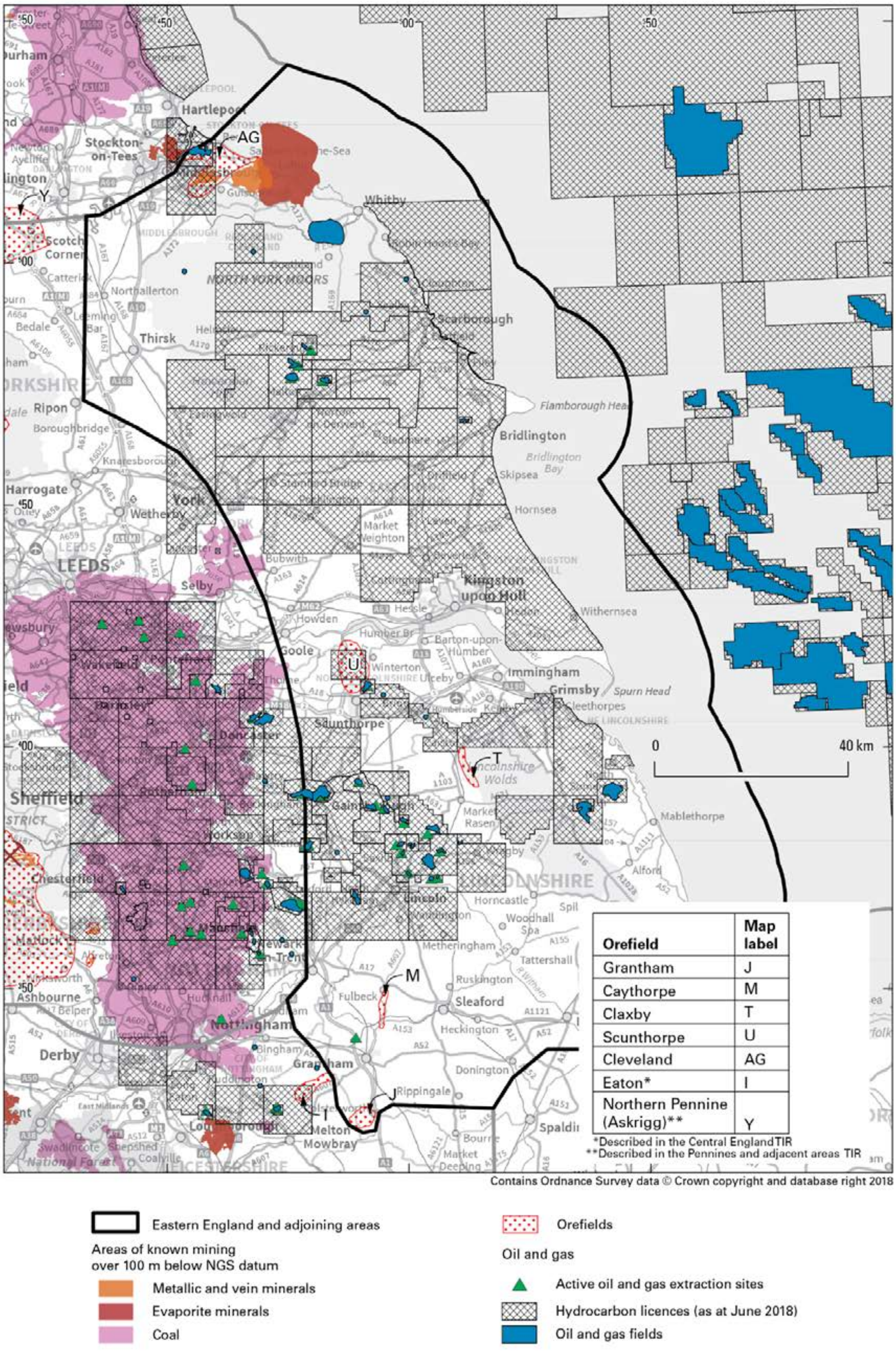

Figure 24 Distribution of mineral resources in the Eastern England region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas 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.

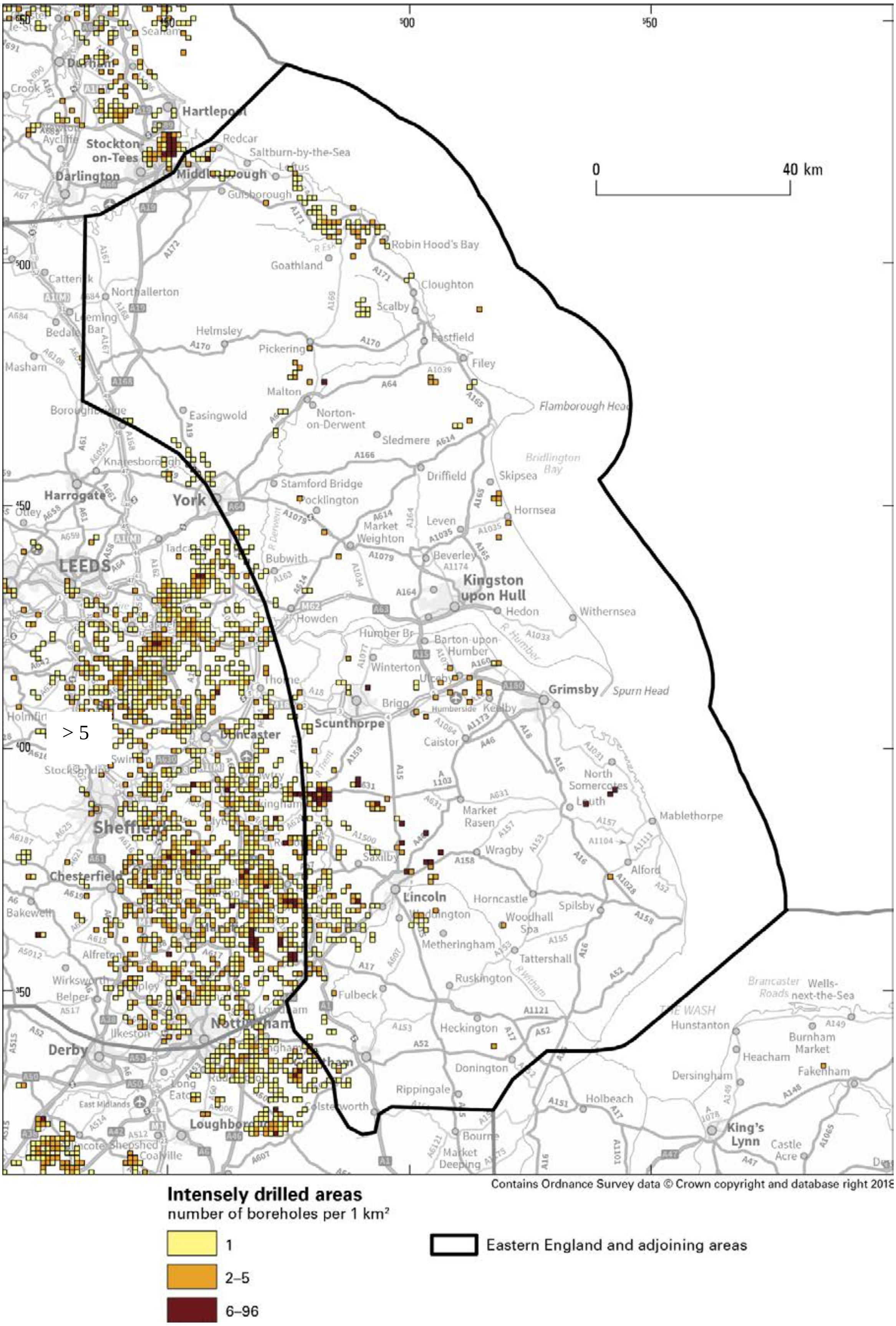

Figure 25 The location of intensely drilled areas in the Eastern England region, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

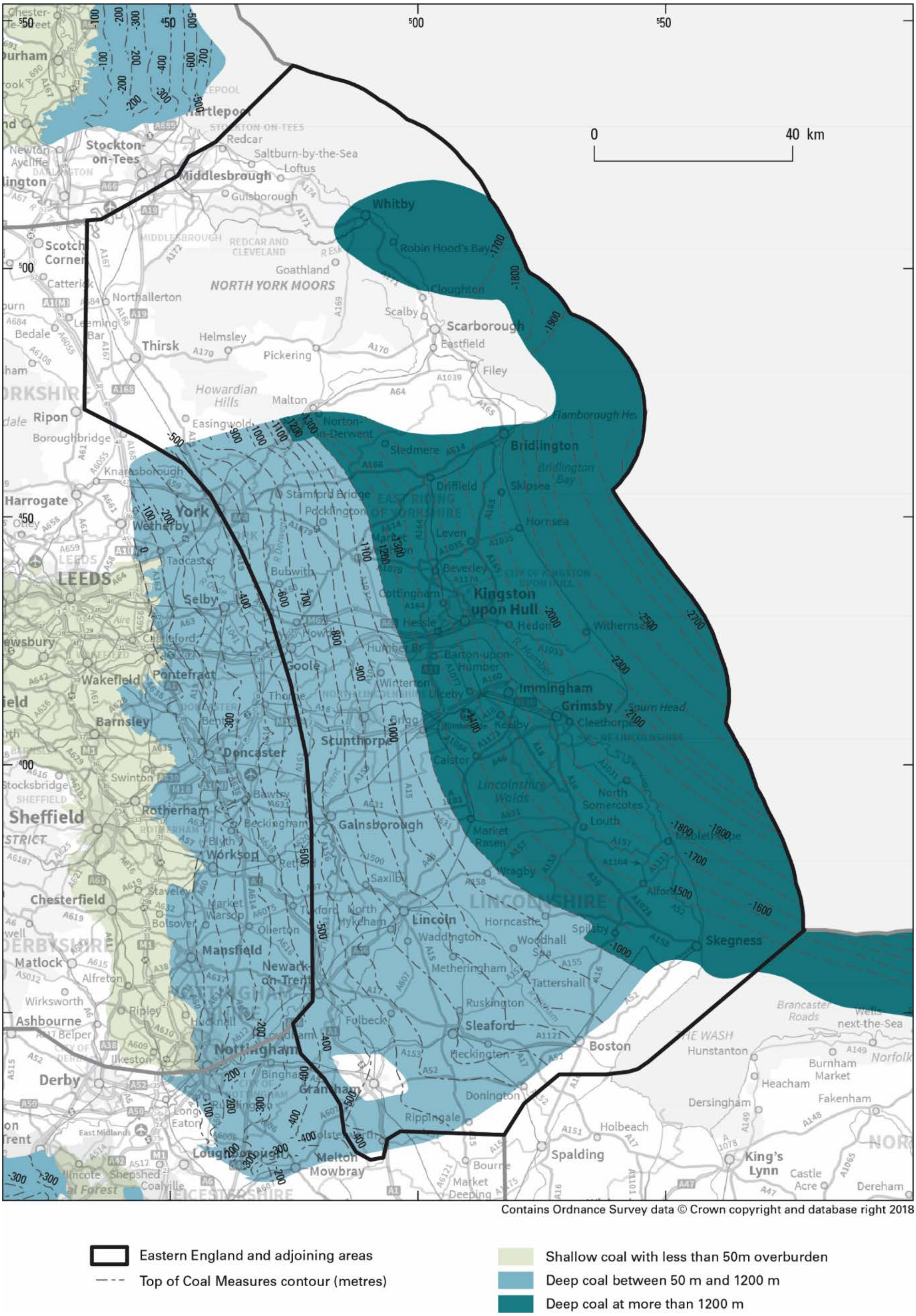

Figure 26 The distribution of coal resources in the Eastern England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

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 are therefore not included in the comprehensive review used to create this dataset. However, it is unlikely these mines will be sufficiently deep to be of concern for NGS.

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 in Figure 24 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 to the location of known mines in order to encompass the possible extent of the workings. This approach ensures that any inaccuracies in the mapped vein locations and extent of past workings fall within the boundary of the area identified.

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

8.11.3 Potash, halite, gypsum, anhydrite and polyhalite deposits

The extent and distribution of these bedded evaporate deposits is largely based on geological interpretation supported by seismic survey information and sporadic 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 24 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 24 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 extent, depth and contained resource of unconventional (shale) gas and oil deposits is less well constrained. The distribution of the prospective rock types is based on geological factors and the potential of this type of deposit in any particular location is dependent on a number of factors such as past burial depth, organic content of the rocks and the practicality of extraction, none of which have been evaluated in the region.

8.11.5 Coal and related commodities

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

Information relating to the depth and distribution of 19th century and later coal mining is generally comprehensive and accurate, more so for workings dating from the mid 19th century onwards when mining legislation was enacted. The location and extent of older coal workings is less well constrained because records are incomplete or non-existent. However, most of these workings are shallow, rarely reaching depths in excess of 100 m below the surface. There is some uncertainty about the depth and distribution of deep, unworked coal because this has not been mined. In many areas it is well constrained by information from seismic surveys and boreholes that were undertaken to assess coal resources, 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 borehole database used records borehole length and not vertical depth. The BGS Single Onshore Borehole Index database also includes a number of boreholes that were drilled from mine galleries, mostly in coal mines, to evaluate coal seams in advance of mining or to assess higher or lower seams. For the purposes of preparing the borehole map it has been assumed that all boreholes are vertical and drilled from the surface. Depth calculations based on these assumptions will tend to be conservative, slightly overestimating maximum depth, and may include or exclude a borehole if collared underground.

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

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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

The locations of coal resources and areas of deep coal mining have been sourced from:

BRITISH GEOLOGICAL SURVEY, CHAPMAN, G R, and COAL AUTHORITY. 1999. *Coal resources map of Britain 1:1 500 000*. (Keyworth: British Geological Survey.)

JONES, N S, HOLLOWAY, S, CREEDY, D P, GARNER, K, SMITH, N J P, BROWNE, M A E, and DURUCAN, S. 2004. UK coal resource for new exploitation technologies: mining and new technologies summary map 1:1 750 000 scale. (Keyworth, Nottingham: British Geological Survey.)

Other bedded mineral resources

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

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

Geothermal energy resources

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

DOWNING, R A, and GRAY, D A. 1986. *Geothermal energy: the potential in the United Kingdom.* (London: HMSO for the British Geological Survey.)

Metallic mineral resources

The locations of deep mines for metallic minerals have been sourced from the BGS 1:1 500 000 metallogenic resources map and BGS economic memoirs such as;

CHAPMAN, S K. 1975. Gazetteer of Cleveland ironstone mines. (Guisborough: Langbaurgh Museum Service.)

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/