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National Geological Screening: East Angalia region

Minerals and Waste Programme

Commissioned Report CR/17/100

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MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/100

National Geological Screening: East Anglia 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 East Anglia region to underpin the process of national geological screening set out in the UK's government White Paper *Implementing geological disposal: a framework for the long-term management of higher activity radioactive waste* (DECC, 2014). The report describes geological features relevant to the safety requirements of a geological disposal facility (GDF) for radioactive waste emplaced onshore and up to 20 km offshore at depths between 200 and 1000 m from surface. It is written for a technical audience but is intended to inform RWM in its discussions with communities interested in finding out about the potential for their area to host a GDF.

Contents

FIGURES

TABLES

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.

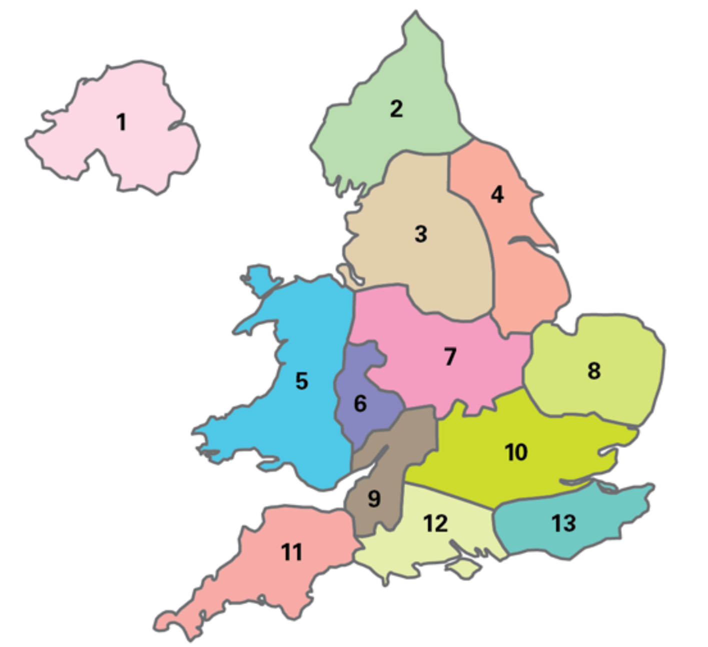
Principal aquifer — a regionally important aquifer defined by the Environment Agency as layers of rock that have high intergranular and/or fracture permeability, meaning they usually provide a high level of water storage (Environment Agency, 2013).

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 East Anglia region (Figure 1).



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

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

2 Background

2.1 NATIONAL GEOLOGICAL SCREENING GUIDANCE

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

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

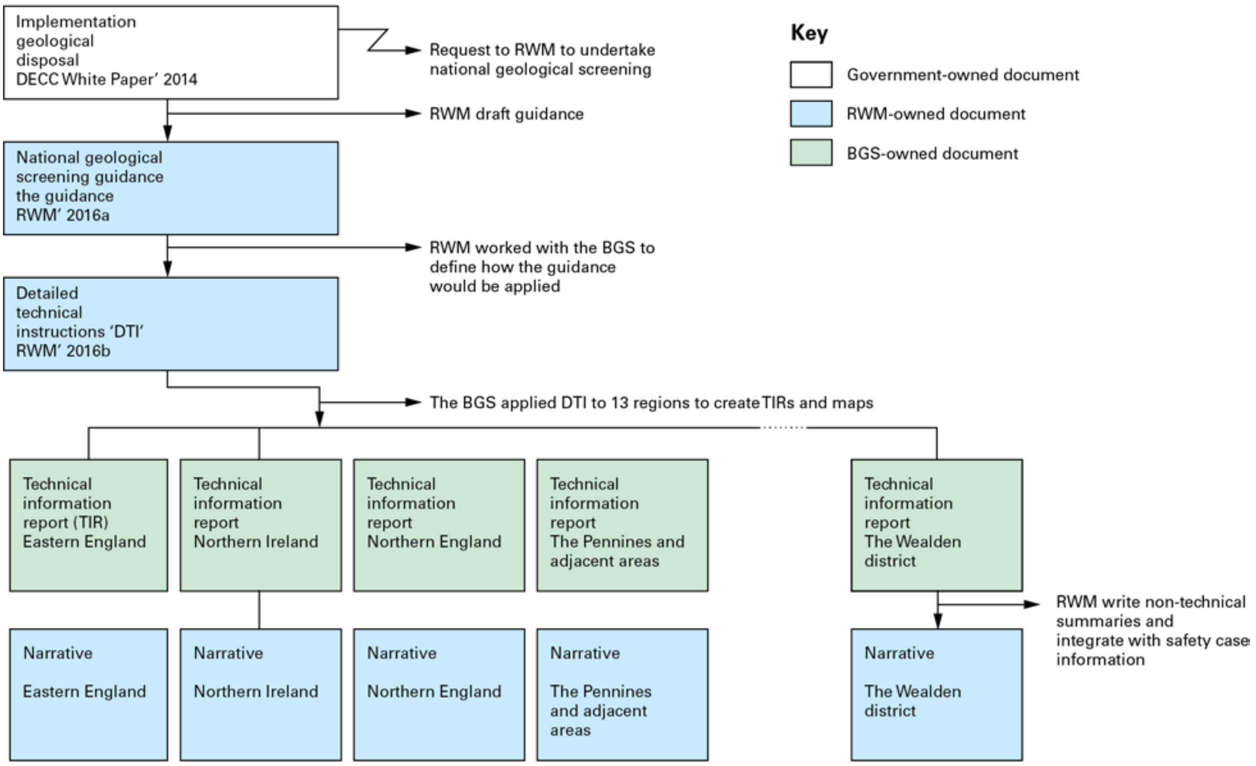


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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

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

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

2.2 DETAILED TECHNICAL INSTRUCTIONS

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

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

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

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

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

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

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

i. **Rock type**

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

ii. **Rock structure**

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

iii. **Groundwater**

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

iv. **Natural processes**

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

v. **Resources**

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

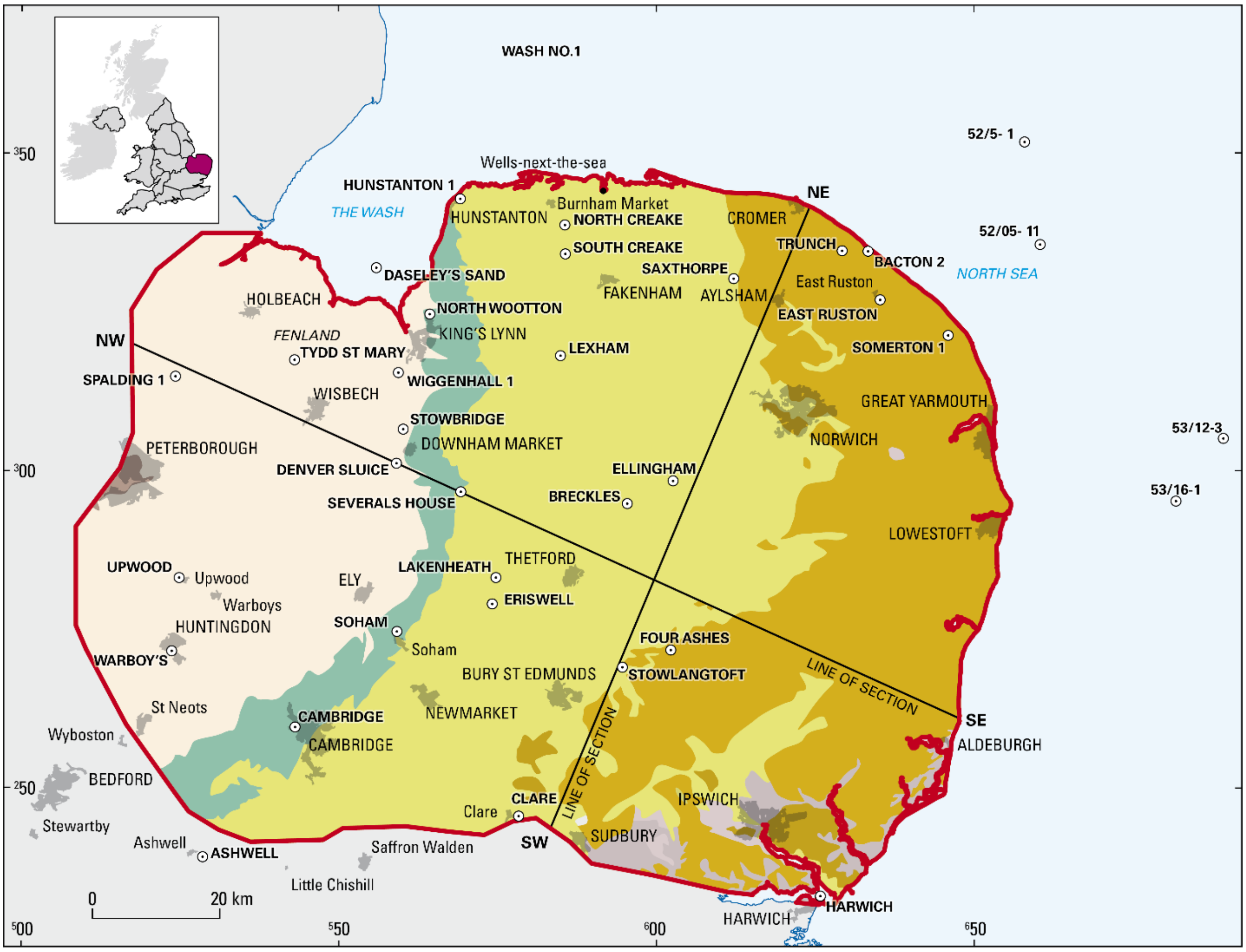
3 The East Anglia region

The East Anglia region is largely defined by the counties of Suffolk, Norfolk, Cambridgeshire, and Bedfordshire, together with part of south Lincolnshire extending around the southern margin of The Wash, near Spalding (Figure 3). The surface bedrock geological succession is dominated by sedimentary rocks, comprising mudstones, sandstones, siltstones and limestones, and admixtures of these, ranging in age from Mid–Late Jurassic in the western part of the region, Cretaceous in the central part, and Cenozoic along the eastern margin (Figure 3). Older strata (late Precambrian to Early Jurassic), proved in boreholes and inferred from geophysical and gravity data, also include crystalline igneous, volcanic and metamorphic rocks, and locally thick evaporites (including halite), the latter being largely confined to boreholes drilled in the Southern North Sea adjacent to the region.

3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

The geology at surface in the region is shown in Figure 3 and Figure 4 illustrates 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.

The near-surface geological structure is relatively simple (Figure 3), with a gentle eastward dip causing progressively younger units to crop out in succession from west to east, with few significant faults developed at rock head. At deeper levels there are patterns of lateral thinning and changes in the physical character of geological units that might not be predicted from the simple near-surface structure. These changes reflect a strong environmental gradient across the region for much of its late Palaeozoic and Mesozoic history, influencing conditions of rock deposition. These changes were driven partly by the wider influence of patterns of uplift and subsidence in the Southern North Sea, and partly by the incorporation of the East Anglia region into a rigid structural block (London–Brabant massif) in the early part of its geological history (Ordovician; around 485–443 million years ago), during a period of amalgamation of micro-continental fragments (Woods, 2015a). Evidence for this deeper, more complex ‘geological basement’ comes from regional gravity data and strongly deformed and faulted late Proterozoic and early Palaeozoic rocks in deep boreholes (Smith and Thomas, 2015). The general effect of this structure was a propensity for the East Anglia region to experience either shallow marine or terrestrial conditions (or oscillations between these) for much of its later geological history. Consequently, the geological successions developed in close proximity to these crustal structures may show unusual or unpredictable patterns of thickness and physical characteristics.



Age (Ma)	Map/section descriptor	Geological sub-units	Text descriptor
1–3	Quaternary to Neogene sediments	Crag Group	Younger sedimentary rocks
50–150	Palaeogene sediments	Thames Group Lambeth Group Thanet Formation	
	Late Cretaceous sedimentary rocks	Chalk Group	
	Early Cretaceous sedimentary rocks	Upper Greensand Formation Gault Formation Lower Greensand Group Wealden Group	
150–200	Mid–Late Jurassic sedimentary rocks	Ancholme Group: Ampthill and Kimmeridge Clay formations, Kellaways and Oxford Clay formations Oolite groups	
	Early Jurassic sedimentary rocks	Lias Group	
210–250	Triassic sedimentary rocks	Mercia Mudstone Group Sherwood Sandstone Group	
250–300	Permian sedimentary rocks	Rotliegendes Group Zechstein Group Warwickshire Group	
300–410	Carboniferous and Devonian rocks	Pennine Coal Measures Group Carboniferous Limestone Supergroup	Older sedimentary rocks
410–550	Lower Palaeozoic rocks	Various Silurian to Cambrian rocks	Basement rocks
	Ordovician–Proterozoic	Granitic intrusions	

Figure 3 Generalised geological map and key showing the distribution of younger sedimentary rocks, older sedimentary rocks and basement rocks in the onshore East Anglia region. It should be noted that the Wealden and Lower Greensand Groups are largely absent in East Anglia, and are mainly represented by separate, ungrouped formations. Upper Greensand is not present in the East Anglia region, where contemporaneous strata are the upper part of Gault and upper part of the Hunstanton Formation. The inset map shows the extent of the region in the UK. See Figure 4 for schematic cross-sections. The 'Geological sub units' column is highly generalised and does not represent all geological units in the region. Stratigraphical nomenclature and lithological descriptions are simplified and 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

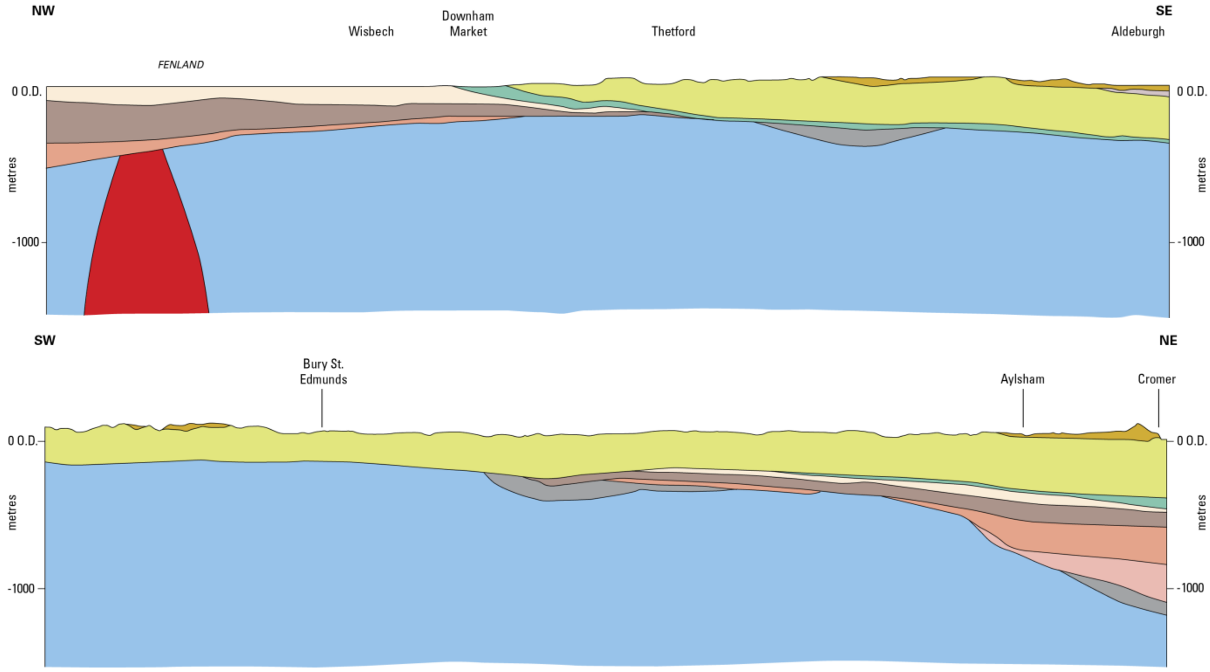


Figure 4 Schematic north-west to south-east and south-west to north-east cross-sections through the East Anglia region. Lines of the sections and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290' British Geological Survey © 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 EAST ANGLIA REGION

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

For the East Anglia region, the GVS groups the rocks into three age ranges: younger sedimentary rocks (Quaternary, Neogene, Palaeogene, Cretaceous, Jurassic, Triassic and Permian), older sedimentary rocks (Carboniferous and Devonian) and basement rocks (Table 3, Column 1). The rocks in the region are predominantly sedimentary in origin. 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) in the younger and older sedimentary rocks as well as higher strength rock (HSR) PRTIs in the basement rocks.

Numerous potential LSSRs, including the Thames Group, Lambeth Group, and undivided Palaeogene sedimentary rocks, in this region are not considered to extend to the depth range of interest that is considered suitable for them to be PRTIs and hence are not discussed further. Strata that are represented by the Wealden Group elsewhere, although a LSSR PRTI in other regions are not considered one in East Anglia as the unit is dominated by sandstone and siltstone. The Zechstein Group rocks (potential evaporite PRTIs) which occur within the region are sandstone dominated rendering them unsuitable as a host rock and are therefore not considered further. Early Palaeozoic mudstone-dominated sedimentary rocks occurring within the basement in the region, 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, proved in boreholes and inferred from geophysical and gravity data, preserves a pervasive cleavage, and therefore is sufficiently compacted and metamorphosed (see Table 2). Consequently they are not considered to be a 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 East Anglia (Lee et al., 2015) and other published sources (see references). They may include terminology or nomenclature that has been updated since those publications were released. The term ‘mudstone’ follows BGS usage to include claystone and siltstone-grade siliciclastics (Hallsworth and Knox, 1999). The location of boreholes referred to in this chapter is shown on Figure 3.

The UK3D model (see glossary) was used as an information source for estimating the presence, thickness, depth of occurrence of geological units discussed below, and the geometry of their boundaries. Interpretations based on this model rely on borehole-derived geological relationships depicted in cross-sections, and it is possible that understanding of these relationships in some areas may be limited by cross-section data availability. Boreholes illustrated by Cameron et al. (1992) in the Southern North Sea proving Permian and Triassic successions lack borehole depth data, and the units described (based on geophysical log correlations) cannot easily be identified on the available lithological logs. Where the Permian and Triassic stratigraphy of these boreholes is described, the absence of depth data is indicated. Some of these offshore boreholes may be inclined, further complicating interpretation of the true vertical depth of occurrence of key stratigraphical intervals in the Southern North Sea.

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

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

Geological period		Geological unit identified in NGS3D	Dominant rock type	Potential rock types of interest			Principle aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS	Quaternary–Neogene	Crag Group	Sandstone, in part ferruginous, shelly, micaceous and gravelly	N/A	N/A	N/A	Crag Group
YOUNGER SEDIMENTARY ROCKS	Palaeogene	Thames Group	Sandstone, siltstone, claystone, locally with volcanic ash horizons and flint gravel	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Palaeogene	Lambeth Group	Clayey glauconitic sandstone, siltstone, and silty claystone	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Palaeogene	Thanet Formation (Montrose Group)	Glauconitic and silty claystone with volcanic ash layers, siltstone, sandstone, flint conglomerate	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Cretaceous	Chalk Group	Fine-grained limestone, with thin units of calcareous mudstone and flint	N/A	N/A	N/A	White Chalk Subgroup
YOUNGER SEDIMENTARY ROCKS	Cretaceous	Gault Formation (and equivalent Hunstanton Formation)	Mudstone and silty mudstone with phosphatic pebbles (Gault Formation); ferruginous sandy limestone and muddy limestone (Hunstanton Formation)	N/A	Gault Formation	N/A	Cromer Knoll Group
YOUNGER SEDIMENTARY ROCKS	Cretaceous	Lower Greensand Group (= Woburn Sands and Sutterby Marl formations)	Sandstone with thin units of Fuller's Earth, phosphatic sandstone and thin limestone (Woburn Sands Formation); calcareous mudstone (Sutterby Marl Formation)	N/A	N/A	N/A	Kings Lynn area only
YOUNGER SEDIMENTARY ROCKS	Cretaceous	Wealden Formation (Roach Formation*)	Clayey, pebbly sandstone with phosphatic and ironstone nodules	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Cretaceous	Dersingham Formation*	Rhythmically interbedded sandstones, siltstones and mudstones	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic to Cretaceous	Sandringham Sands Formation*	Pyritic, glauconitic and clayey sandstone, with horizons of phosphatic nodules and ironstone	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Kimmeridge Clay, Ampthill Clay and West Walton formations (Ancholme Group	Mudstone, silty mudstone, siltstone, with thin limestones and occasional ironstone	N/A	Kimmeridge Clay, Ampthill Clay and West Walton formations	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Oxford Clay Formation, Kellaways Clay Member (Ancholme Group)	Mudstone, silty mudstone, siltstone, with thin limestones and occasional ironstone	N/A	Oxford Clay Formation, Kellaways Clay Member	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Great Oolite Group	Mudstone, muddy limestone, limestone, sandstone	N/A	N/A	N/A	Blisworth Limestone Formation
YOUNGER SEDIMENTARY ROCKS	Jurassic	Inferior Oolite Group	Limestone, ferruginous limestone, mudstone, siltstone, sandstone	N/A	N/A	N/A	Lincolnshire Limestone Formation
YOUNGER SEDIMENTARY ROCKS	Jurassic	Lias Group	Mudstone, limestone, siltstone, sandstone, locally including ironstone	N/A	Whitby Mudstone and Charmouth Mudstone formations	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Triassic	Mercia Mudstone Group (onshore) / Haisborough Group (offshore)	Pebbly sandstone, siltstone, mudstone with anhydrite (onshore); siltstone and mudstone with anhydrite and halite (offshore)	N/A	Mercia Mudstone Group	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Triassic	Sherwood Sandstone Group (onshore) / Bacton Group (offshore)	Sandstone, mudstone and conglomerate (Sherwood Sandstone Group) sandstone, siltstone and mudstone (Bacton Group)	N/A	Bacton Group	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Permian	Undifferentiated Permian rocks (onshore); Rotligendes and Zechstein groups (offshore)	Mudstone, sandstone, siltstone, conglomerate (onshore); sandstone, siltstone, mudstone, dolomitic limestone, halite, anhydrite (offshore)	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous to Permian	Warwickshire Group	Siltstone and sandstone with subordinate mudstone	N/A	Warwickshire Group	N/A	N/A
OLDER SEDIMENTARY ROCKS	Caboniferous	Tournaisian–Visean rocks (Carboniferous Limestone Supergroup)	Limestone and dolomitic limestone with interbedded mudstone	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Caboniferous	Coal Measures Formation	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Caboniferous	Millstone Grit Group	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Devonian	Late and Early Devonian rocks	Mudstone, siltstone, sandstone, conglomerate	N/A	N/A	N/A	N/A
BASEMENT ROCKS	Early Palaeozoic	Silurian rocks	Mudstone, sandstone, siltstone	N/A	N/A	N/A	N/A
BASEMENT ROCKS	Early Palaeozoic	Ordovician rocks	Sandstone, siltstone, mudstone and recrystallised ash-flow tuffs	N/A	N/A	N/A	N/A
BASEMENT ROCKS	Early Palaeozoic	Cambrian rocks	Metamorphosed sandstone (quartzite) and mudstone (phyllite)	N/A	N/A	N/A	N/A
BASEMENT ROCKS	Early Palaeozoic	Igneous intrusive rocks—variable (many of probable Ordovician age)	Granite, granodiorite and calc-alkaline intrusive igneous rocks	Intrusive rocks	N/A	N/A	N/A
BASEMENT ROCKS	Neoproterozoic	Avalonian crystalline igneous rocks	Welded ash-flow tuff	Ash-flow tuff	N/A	N/A	N/A

* It should be noted that the Wealden and Lower Greensand Groups are largely absent in East Anglia, and are mainly represented by separate, ungrouped formations. Upper Greensand is not present in the East Anglia region, where contempraneous strata are the upper part of Gault and upper part of the Hunstanton Fomation.

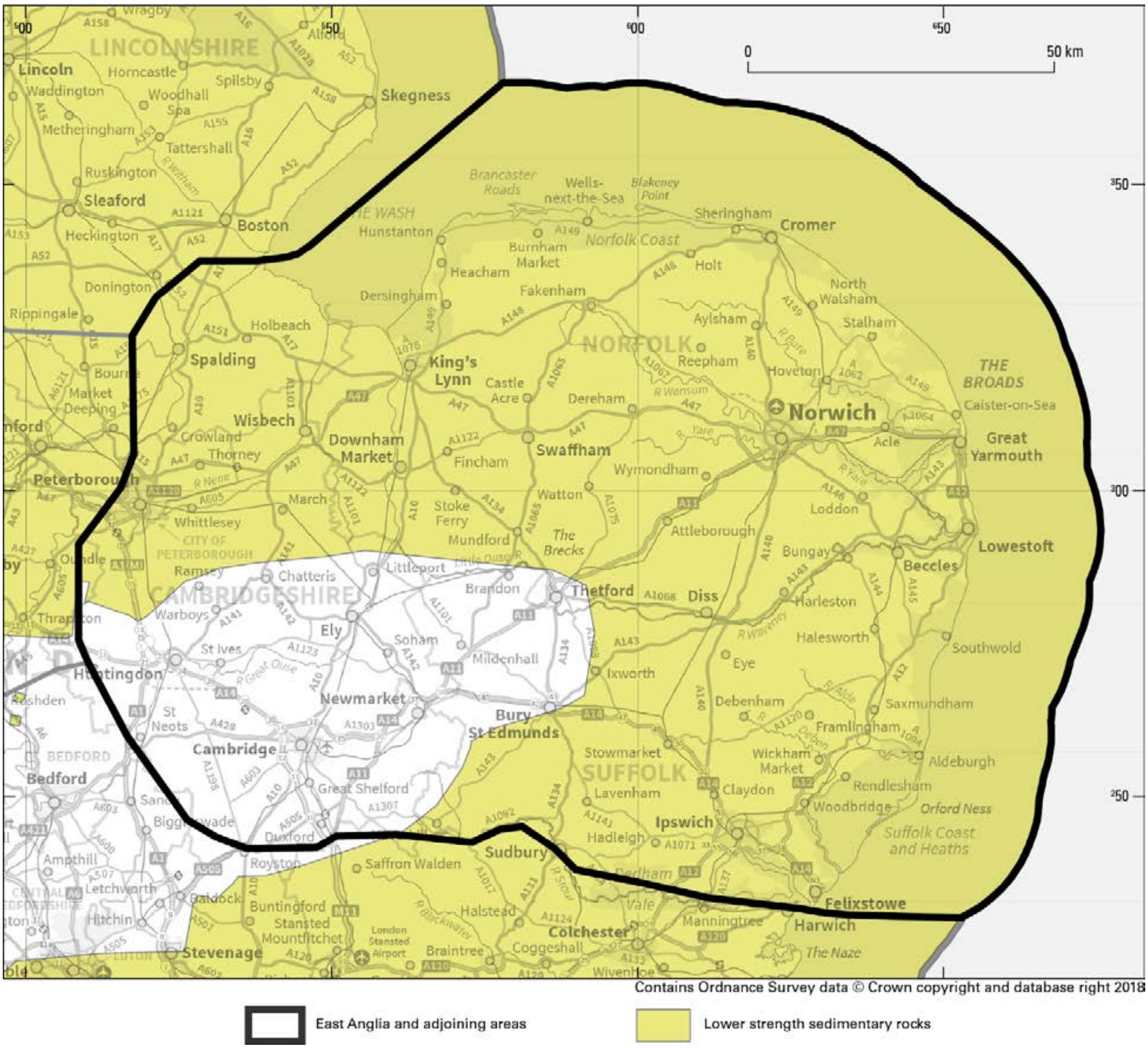


Figure 5 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the East Anglia region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290' British Geological Survey © UKRI 2018

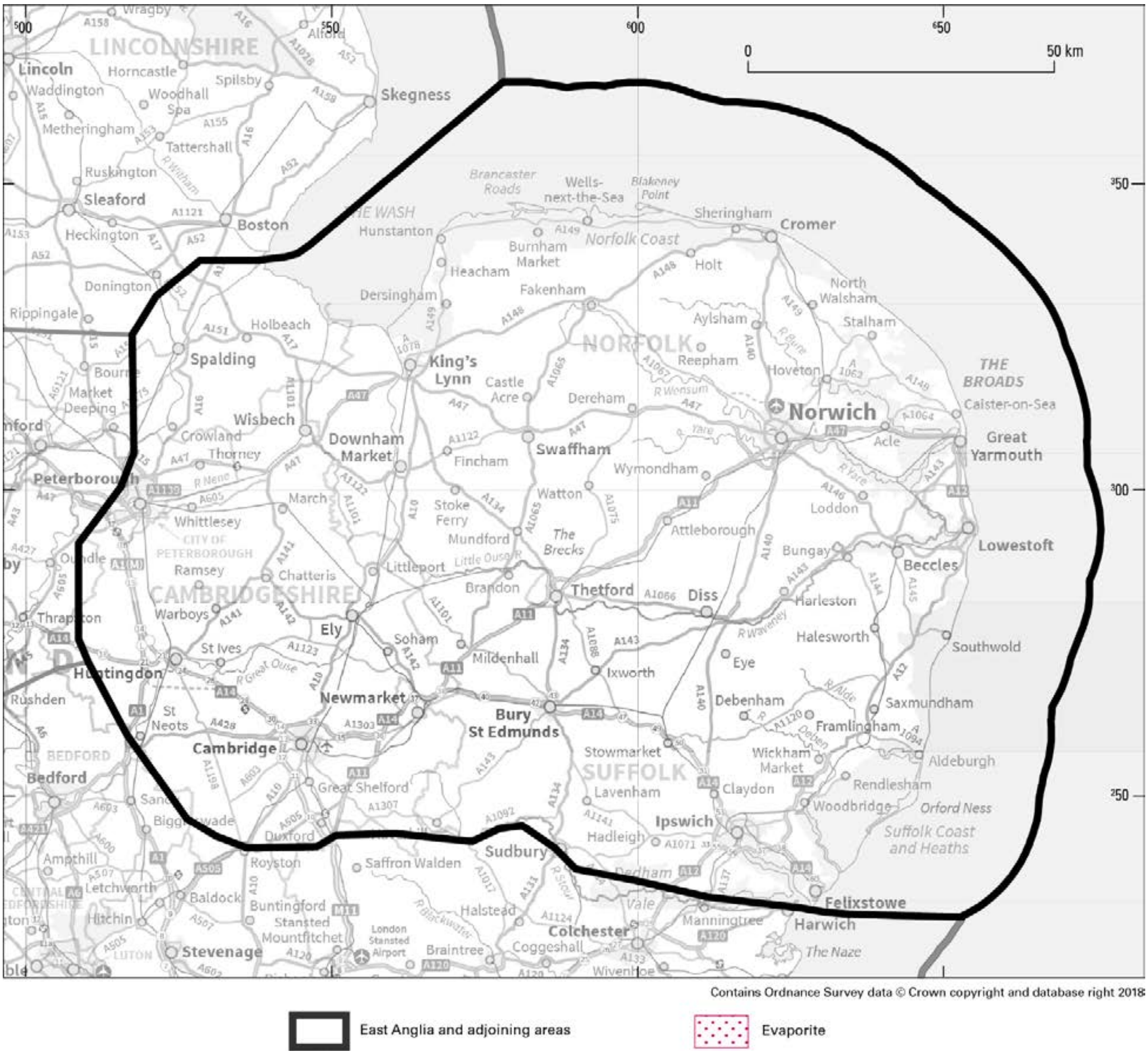


Figure 6 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the East Anglia region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290' British Geological Survey © UKRI 2018

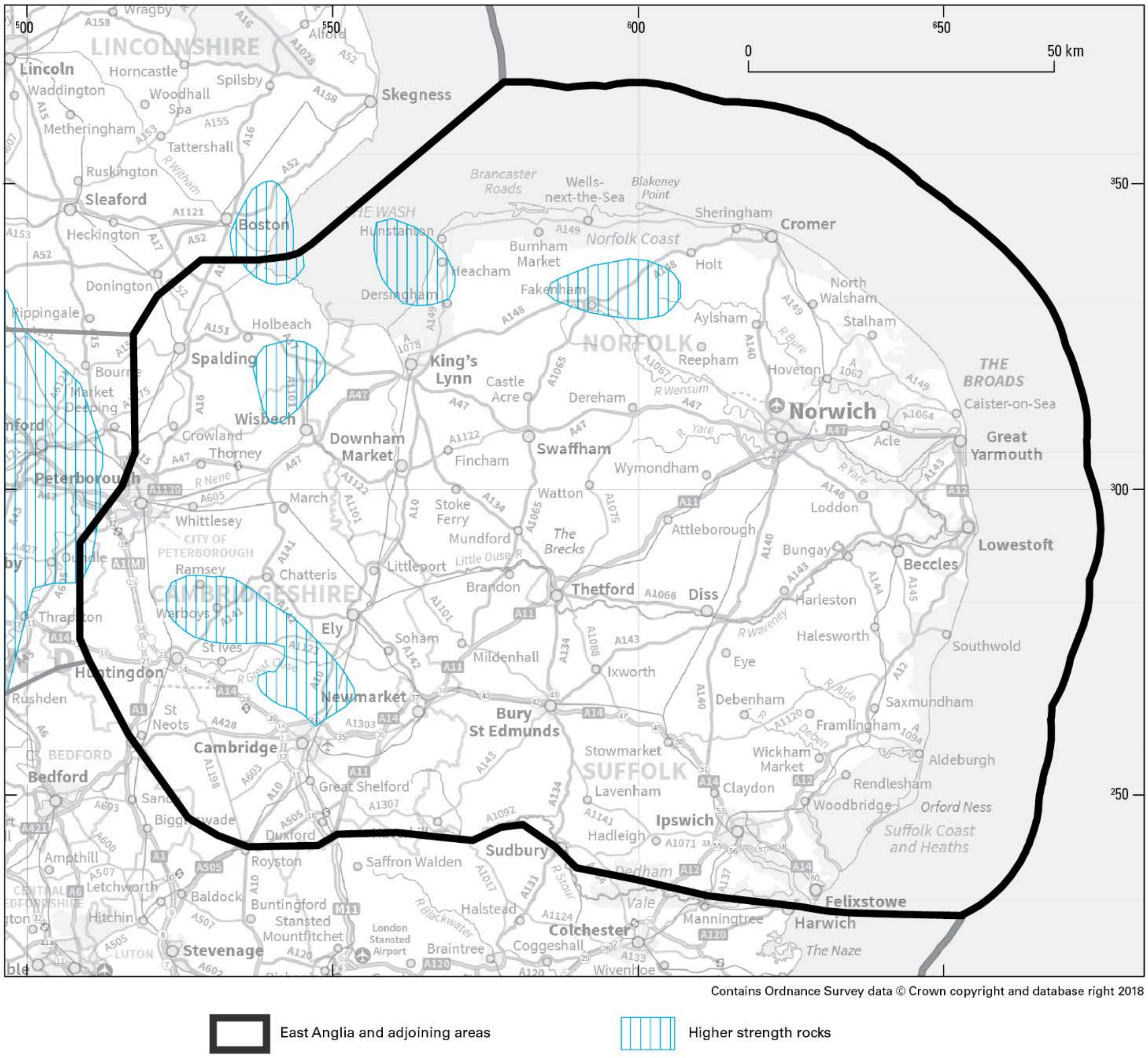


Figure 7 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the East Anglia region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290' British Geological Survey © UKRI 2018

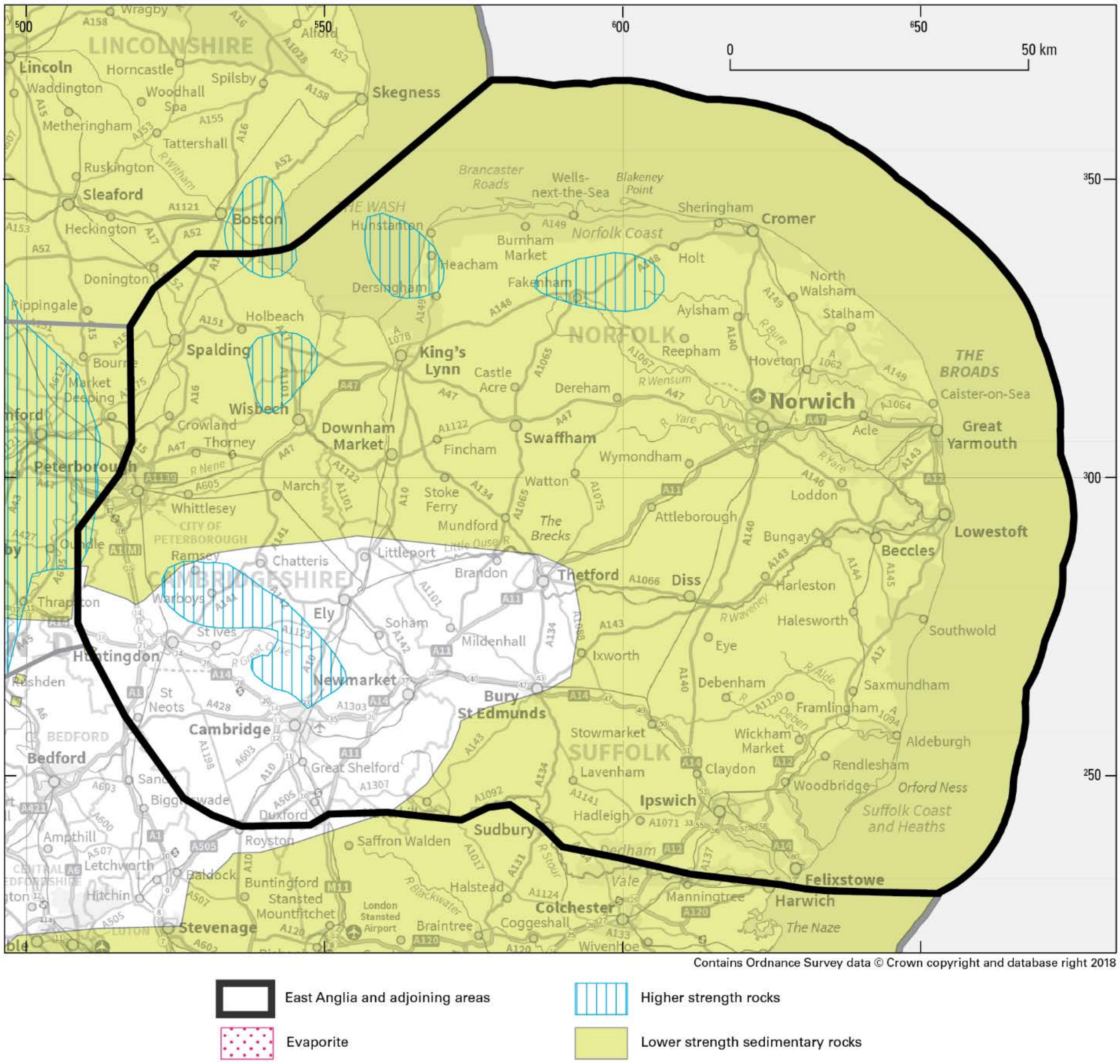


Figure 8 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the East Anglia region. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290' British Geological Survey © UKRI 2018

4.2.1 Younger sedimentary rocks

4.2.1.1 Gault Formation — LSSR

The Gault Formation is a mudstone-dominated succession with subordinate siltstone, minor limestone units, and frequent phosphate nodules beds (Gallois and Morter, 1982; Pattison et al., 1993; Bristow, 1990; Gallois, 1988, 1994; Arthurton et al., 1994). The outcrop of the formation forms a thin linear band in the western part of the region, running approximately north–south between King's Lynn and Downham Market, and thence south-westwards towards Cambridge and the southern limit of the region. Where seen at outcrop and in boreholes, the Gault has been informally divided into upper and lower parts (Upper Gault, Lower Gault) on the basis of a regionally developed erosion surface, typically marked by a concentration of silty mudstone with glauconite and phosphatic nodules. Whilst the Upper Gault comprises pale calcareous mudstone, including thin, locally developed limestones, the Lower Gault is generally developed as dark to medium grey mudstone (Woods, 2015b). Many of the phosphatic nodule beds mark erosion surfaces which have been recognised as defining depositional cycles comprising (in ascending order): erosion surface, phosphatic nodule bed, silty mudstone, medium grey mudstone and pale grey mudstone (Gallois and Morter, 1982).

Information about the detailed character of the Gault is mainly provided by numerous boreholes drilled for water, hydrocarbons and site investigations across East Anglia. The detailed stratigraphy seen in some of these boreholes has been reported on by Gallois and Morter (1982), in BGS memoirs (Pattison et al., 1993; Bristow, 1990; Gallois, 1988, 1994; Arthurton et al., 1994), and synthesised in the recently published British Regional Geology guide for East Anglia (Lee et al., 2015).

Only in the south-east of the region, approximately in the arcuate region south and east of a line drawn between Great Yarmouth, Norwich, Thetford, Bury St Edmunds, Sudbury and Colchester, does geological modelling (NGS3D Model) and borehole data indicate that the formation largely falls within the depth range of interest. Northwards across north Norfolk, strata equivalent to the Gault that occur within the range of interest, are represented by thin, ferruginous limestones of the Hunstanton Formation (Gallois and Morter, 1982).

Where the Gault occurs within the depth range of interest in central East Anglia, for example in the Breckles Borehole, the Gault is 12.5 m thick, and similarly in the Stowlangtoft Borehole, near Bury St Edmunds, where the Gault is 13.5 m thick and occurs below 211.45 m depth (Bristow, 1990). South-eastwards, the Clare Borehole near the southern margin of the East Anglia region shows the Gault is present below 221.2 m and is 11.1 m thick, increasing to 18.6 m at the south-eastern edge of the East Anglia region in the Harwich Borehole. The boreholes at Stowlangtoft and Clare are fully cored, allowing confident interpretation of the formation and thickness at these localities.

Across the whole of the East Anglia region, outcrop and borehole data suggests a complex pattern of thinning and thickening, probably largely due to the influence of the London–Brabant massif on depositional conditions, but possibly also influenced by fault-induced subsidence at the margins of this structure (Woods et al., 1995; Figure 9). Eastwards, in the subsurface, there is a general trend of thinning, seen, for example, in borehole successions at Four Ashes and Stowlangtoft (Gallois and Morter, 1982; Bristow, 1990; Figure 9). In the Clare Borehole, near Sudbury, the lower part of the Gault is almost entirely absent (Pattison et al, 1993; Figure 9).

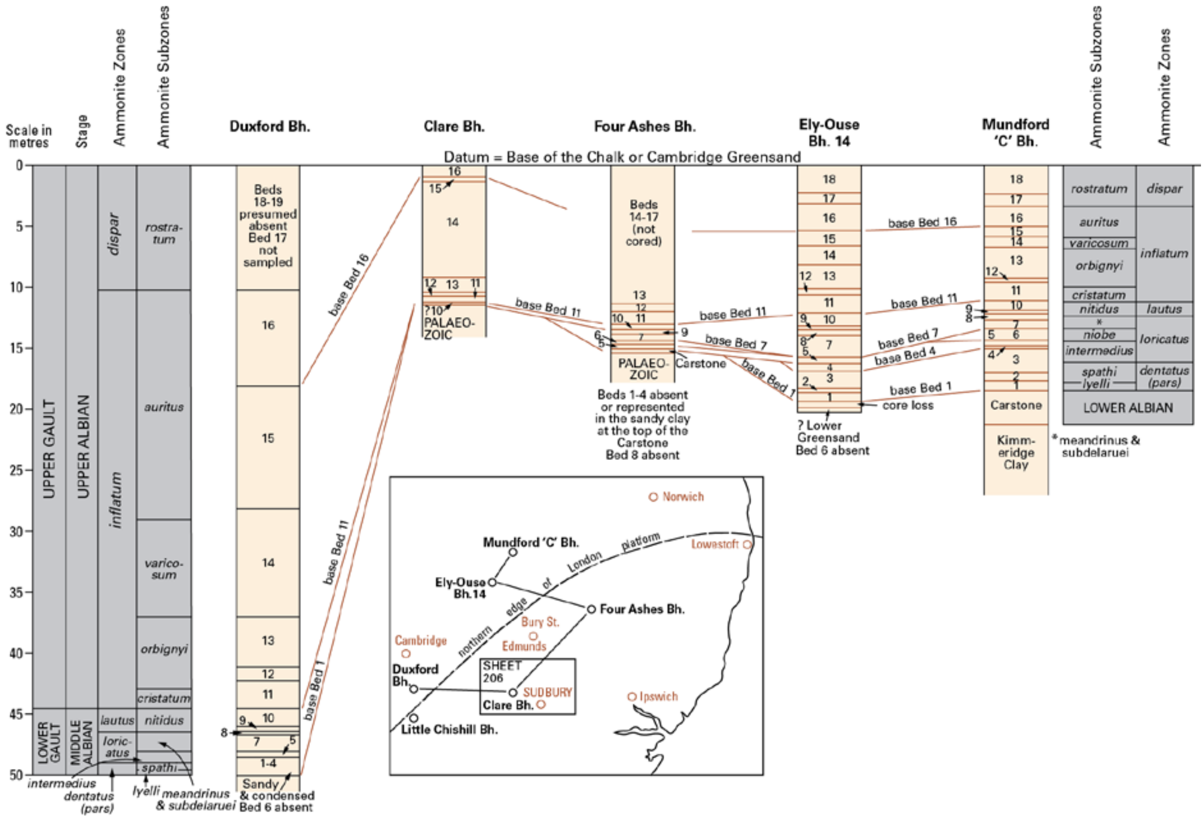


Figure 9 Correlation and thickness variation of the Gault Formation of East Anglia (from Pattison et al., 1993 Figure 9). British Geological Survey © UKRI 2018

4.2.1.2 Undivided Ancholme Group comprising West Walton, Ampthill Clay And Kimmeridge Clay formation and the undivided Kellaways And Oxford Clay Formations— LSSR

The Ancholme Group comprises a suite of mudstone-dominated geological units that crop out along the western margin of the East Anglia region, adjacent to The Wash and extending south-westwards to Bedford and beyond. The subcrop is widest in the northern part of the East Anglia region, (as seen in the Saxthorpe Borehole), and possibly extends eastwards to within 20 km of Norwich. Southwards the subcrop narrows towards Cambridge and Bedford (Barron, 2015; Figure 10), and the Group is absent in the Ashwell Borehole, south-west of Cambridge. In NGS3D, the Ancholme Group is divided into two modelled units, the West Walton Formation, Ampthill Clay Formation and Kimmeridge Clay Formation (undivided) above, and the Kellaways Formation and Oxford Clay Formation (undivided) below.

The units comprising the Ancholme Group are (in descending order) Kimmeridge Clay Formation, Ampthill Clay Formation, West Walton Formation, Oxford Clay Formation and Kellaways Formation (Barron, 2015, Figure 11), Collectively, these units possibly exceed 250 m in thickness in the vicinity of The Wash, with 237 m proved in the Hunstanton 1 Borehole. South-eastwards, borehole data suggests that all these units thin strongly and eventually become absent (NGS3D Model). The top of the Ancholme Group is an unconformity (erosion surface) marking the contact with Cretaceous strata.

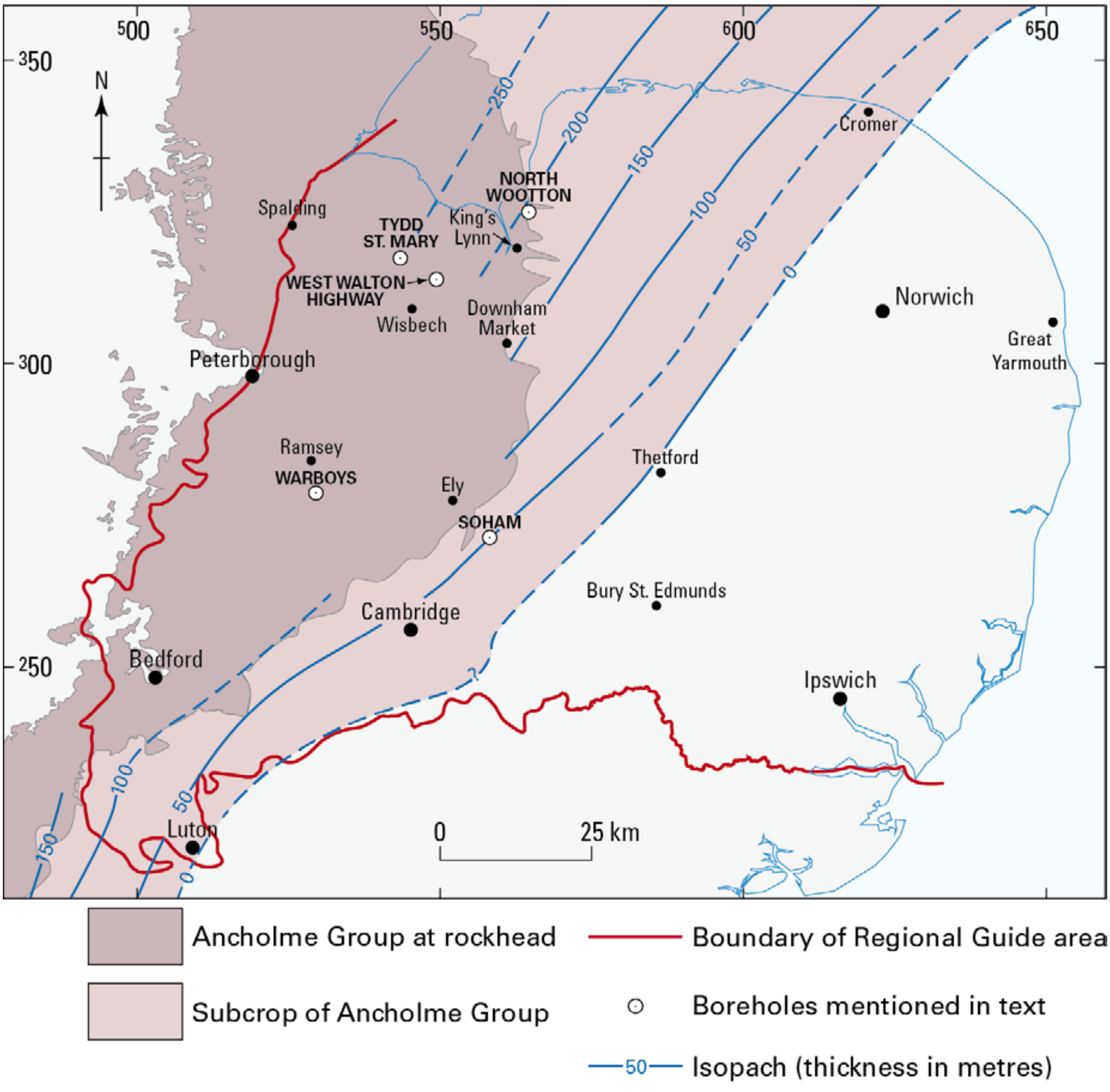


Figure 10 Thickness variation of the Ancholme Group (from Barron, 2015, fig. 23). Pecked lines denote uncertainty. British Geological Survey © UKRI 2018

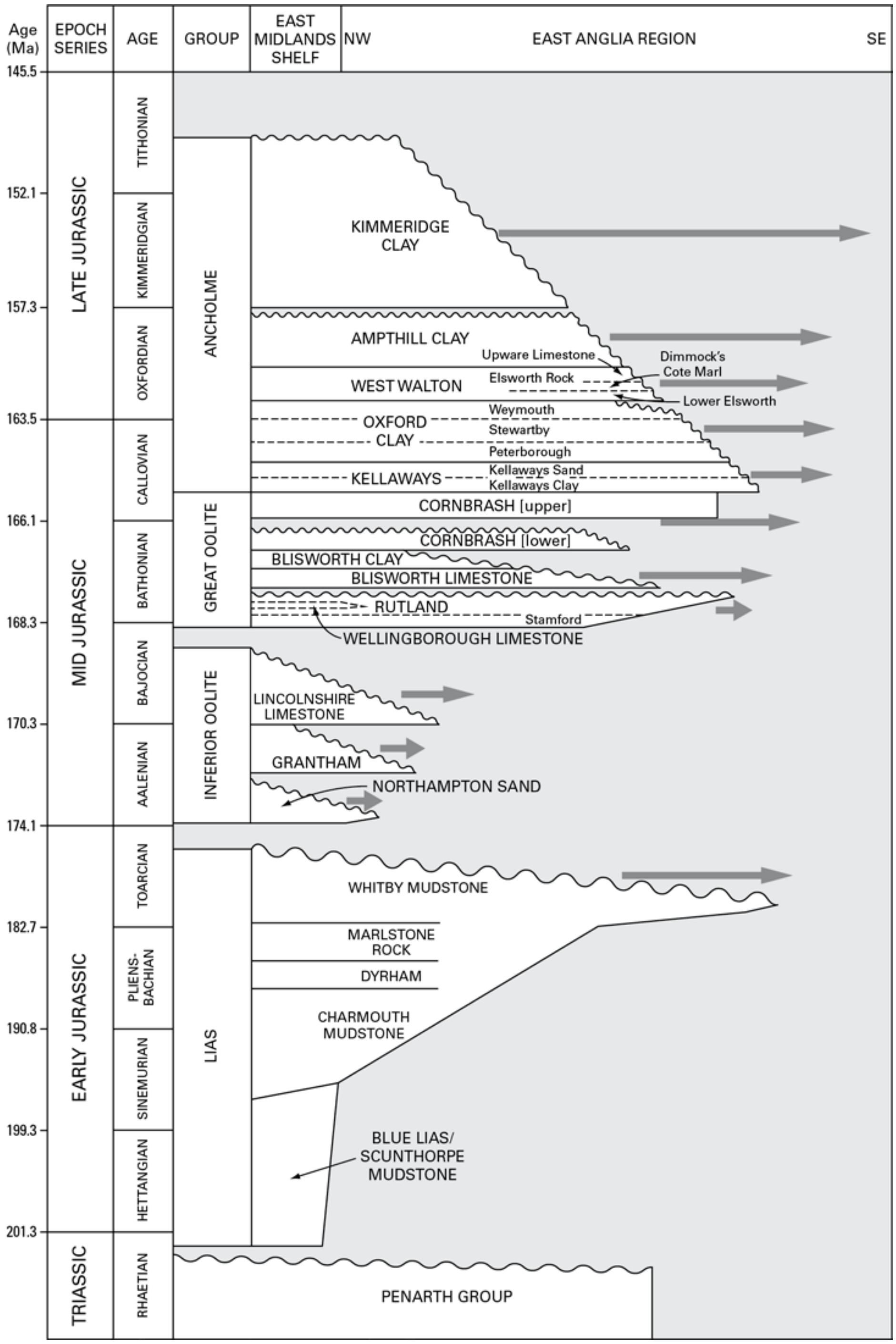


Figure 11 Jurassic stratigraphy of the East Anglia region (from Barron, 2015, fig. 20). British Geological Survey © UKRI 2018

Information about the units comprising the Ancholme Group across East Anglia is provided by BGS memoirs for King's Lynn and The Wash (Gallois, 1994), Bury St. Edmunds (Bristow, 1990) and Ely (Gallois, 1988); a BGS Research Report on the Eriswell Borehole (Bristow et al., 1989); boreholes drilled in connection with geological investigations for the Wash Water Storage Scheme (Gallois, 1979), and a synthesis of age, lithology and regional thickness variation by Barron (2015) in the recently published British Regional Geology guide for East Anglia (Lee et al., 2015).

Only across a limited part of northern East Anglia is the Ancholme Group within the depth range of interest, extending from The Wash and north Norfolk coast southwards to the Thetford area, and eastwards towards Dereham (about 20 km west of Norwich). Within this region, the group is about 107 m thick in the Lexham

Borehole a few kilometres north-north-east of Swaffham, but near Thetford the thickness of the group within the depth range of interest is reduced to 15 to 20 m (NGS3D Model).

Understanding the thickness pattern of component units of the Ancholme Group within the depth window of interest is prevented by lack of geological model resolution. Additionally, local variations in depositional conditions and/or patterns of erosion across the London–Brabant massif might produce local variations in thickness and lithofacies within the subcrop, especially perhaps at the south-eastern (feather-edge) limits of the component units of the Ancholme Group.

Kimmeridge Clay Formation

The Kimmeridge Clay (Figure 12), forming the youngest part of the Ancholme Group, mainly comprises dark and pale grey, calcareous mudstone, with subordinate amounts of silty mudstone/siltstone (around 5 per cent) and muddy limestone ('cementstone', less than 5 per cent) (Barron, 2015). Phosphatic pebbles are mainly present in the lower part and pyrite occurs throughout as replacements of fossils, burrow infills and disseminated within the mudstone (Barron, 2015). At least six, thin 'cementstone' horizons are developed in boreholes near King's Lynn, and organic-rich 'oil shales' are locally developed and have previously been commercially exploited in Norfolk (Gallois, 1979, 2012). Boreholes drilled in the 1970s in connection with a proposed water storage scheme in the area around The Wash proved detailed successions in the Kimmeridge Clay in boreholes at North Wootton, Denver Sluice, Stowbridge and Daseley's Sand (Gallois, 1979). In the North Wooton Borehole oil shales perhaps comprise around 10 per cent of the succession (Gallois, 1979). South-eastwards in the subcrop, borehole data suggests that the Kimmeridge Clay exhibits a more rapid thickness reduction than other units of the Ancholme Group (Barron, 2015; Figure 11 and 12). Since the Kimmeridge Clay Formation is the youngest component of the Ancholme Group, it might be inferred that the subcrop extent of the Group is broadly co-extensive with the top of the Kimmeridge Clay, although this might be affected by local geological structure and locally variable patterns of erosion.

Ampthill Clay Formation

Boreholes drilled in the 1970s around The Wash, near King's Lynn, show that the Ampthill Clay comprises pale, mid and dark grey mudstone, sometimes moderately calcareous and silty, with occasional and locally developed units of limestone ('cementstone') and ironstone, and thin units showing increased organic content (Gallois, 1979; Barron, 2015). These boreholes proved at least 51 m of Ampthill Clay (Gallois, 1979), and across most of the western part of the East Anglia region borehole data suggests that the formation is 50 to 55 m thick; thinner in the Cambridge–Ely area (20 to 30 m), and thin or absent further south in Bedfordshire (Barron, 2015). Like the other constituents of the Ancholme Group, borehole data suggests that the Formation thins and disappears in the subcrop south-eastwards across the East Anglia region (Figure 11).

West Walton Formation

The West Walton Formation comprises a variety of rock types, although mudstone is the dominant component. The succession was described in detail from boreholes drilled in the area of The Wash near King's Lynn (Gallois, 1979). These show alternating calcareous mudstone and silty mudstone, with bands of limestone concretions and burrowed surfaces representing pauses in sediment accumulation (Gallois, 1979; Barron, 2015). The succession can be divided into 16 beds based on sediment and fossil characteristics, and in the area of The Wash is up to 14.5 m thick with at least six units of 'cementstone' (Gallois, 1979); a similar thickness (14.96 m) occurs in a borehole at Eriswell near Mildenhall, Suffolk (Bristow et al., 1989), but here the succession is capped by an erosion surface overlain by Cretaceous strata. Southwards at outcrop, the formation thins to less than 10 m in the Cambridge area, where the succession changes its character to become dominated by alternating silty limestone and calcareous mudstone. Here, the limestone-rich Elsworth Rock Member overlies the mudstone- and limestone-bearing Lower Elsworth Member (Barron, 2015). North-eastwards at Upware, the equivalent of the Elsworth Rock is represented by a coral-rich limestone (Upware Limestone Member) above a more mud-rich succession (Dimmock's Cote Marl Member). The succession thins and disappears south-eastwards across the East Anglia region (Barron, 2015; Figure 11).

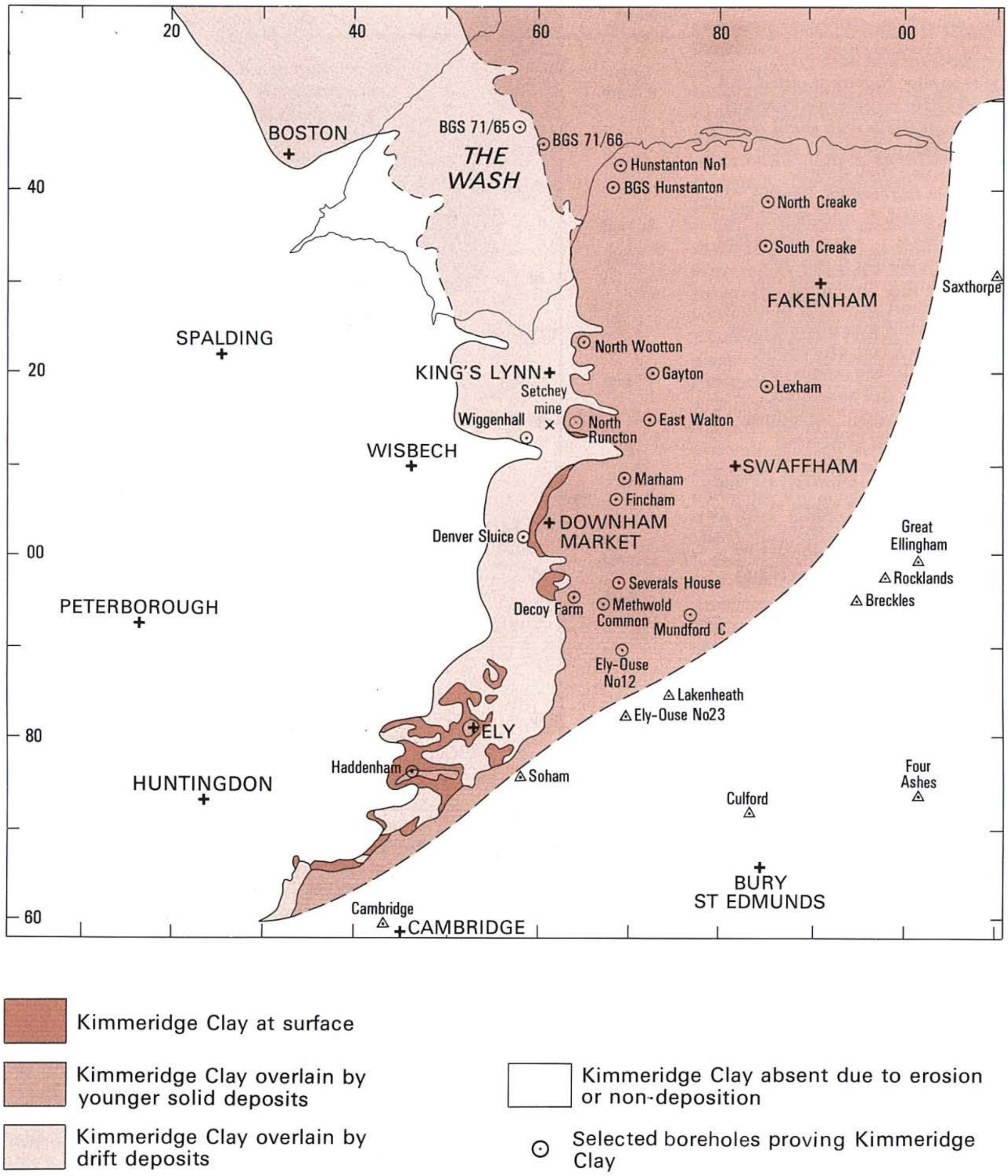


Figure 12 Rockhead and subsurface occurrence of the Kimmeridge Clay Formation in the East Anglia region (from Gallois, 1994, Figure 16). British Geological Survey © UKRI 2018

Oxford Clay Formation

The Oxford Clay Formation is mainly known from brick clay quarry exposures where the formation occurs at outcrop in the western part of the East Anglia region, for example near Peterborough and Bedford. The formation is dominated by mudstone and silty mudstone, organic-rich in the lower part, with bands of limestone concretions that are concentrated towards the middle of the formation (Barron, 2015). Pyrite, often preserving fossils, occurs throughout. In the Spalding Borehole in the north of the district, the Oxford Clay is more than 70 m thick, thinning south-eastwards to 56.4 m in the Tydd St Mary Borehole in west Norfolk, and around 50 m in the Soham Borehole in eastern Cambridgeshire (Barron, 2015; Gallois, 1994).

The Weymouth Member forms the highest part of the Oxford Clay and comprises calcareous, variably silty mudstone with some dark-coloured, organic-rich mudstones, with at least two horizons of 'cementstone' developed in boreholes around The Wash (Gallois, 1979; Barron, 2015). This part of the succession is poorly exposed at outcrop, but borehole and outcrop evidence at Warboys near Huntingdon suggests a maximum thickness here for the Weymouth Member of 30 m; thinner in the north near King's Lynn (around 20 m) and thinning south-east in the subcrop in the Soham Borehole (14.5 m), and removed by erosion below the West Walton Formation in the Eriswell Borehole (Bristow et al., 1989; Barron, 2015). Below this, the middle part of the Oxford Clay is designated the Stewartby Member and is seen in brick pits east of Peterborough and at Stewartby in Bedfordshire (Barron, 2015). The succession lacks organic-rich horizons and is dominated by calcareous, variably silty mudstone, becoming muddy limestone towards the top of the member, where the Lamberti Limestone forms a regionally developed marker bed. Near King's Lynn and The Wash, at least six horizons of 'cementstone' are developed in the Stewartby Member (Gallois, 1979). The member maintains a relatively constant thickness of 20 to 23 m at outcrop along the western margin of the East Anglia region, but south-eastwards, in the subcrop, it is only 9.1 m thick in the Soham Borehole and only 6.92 m thick in the Eriswell Borehole, where it is capped by an erosion surface (Bristow et al., 1989; Barron, 2015).

The lowest part of the Oxford Clay typically includes organic-rich mudstone, known as the Peterborough Member, and contains bands of highly fissile shale alternating with more massive, blocky-weathering mudstone, variably silty, and with regularly developed shell beds and occasional 'cementstones' (Bristow et al., 1989; Hudson and Martill, 1994; Barron, 2015). This part of the formation is relatively thick at outcrop in the south of the region, for example, 23m thick at Bedford compared to 13.9 m near King's Lynn in the north; eastwards it thins to 17.9 m in the Soham Borehole (Barron, 2015) and 10.44 m in the Eriswell Borehole (Bristow et al., 1989; Figure 13).

Kellaways Clay Member (of the Kellaways Formation)

The lower part of the Kellaways Formation is a dark grey, bituminous, laminated silty mudstone, siltier and sandier towards the top, with phosphatic and ferruginous nodules, and pyrite disseminated through the rock and concentrated into burrows (Barron, 2015). Exposures occur in the Nene and Great Ouse river valleys and in quarries worked for brick making around Peterborough and Bedford, and where seen at outcrop the Formation as a whole is typically 5 to 7 m thick with 2.5 to 3 m usually representing the Kellaways Clay (Barron, 2015).

In the western part of the East Anglia region, the Kellaways Clay is mostly above the depth range of interest, for example in the Spalding, Wiggenhall 1 and Tydd St Mary boreholes, but falls within the depth range of interest in the North Creake Borehole in north Norfolk, where it is present at 345 m depth and is about 5 m thick. Further east the Member, in common with the rest of the Ancholme Group, thins and disappears; it is absent in the Bacton 2 Borehole on the north-east Norfolk coast. Further south, little or none of the Kellaways Clay Member is likely to occur within the depth range of interest. It is thin and relatively shallow in the Soham (around 0.5 m at 77.6 m depth) and Upwood (2.36 m at 33.2 m depth) boreholes in Cambridgeshire.

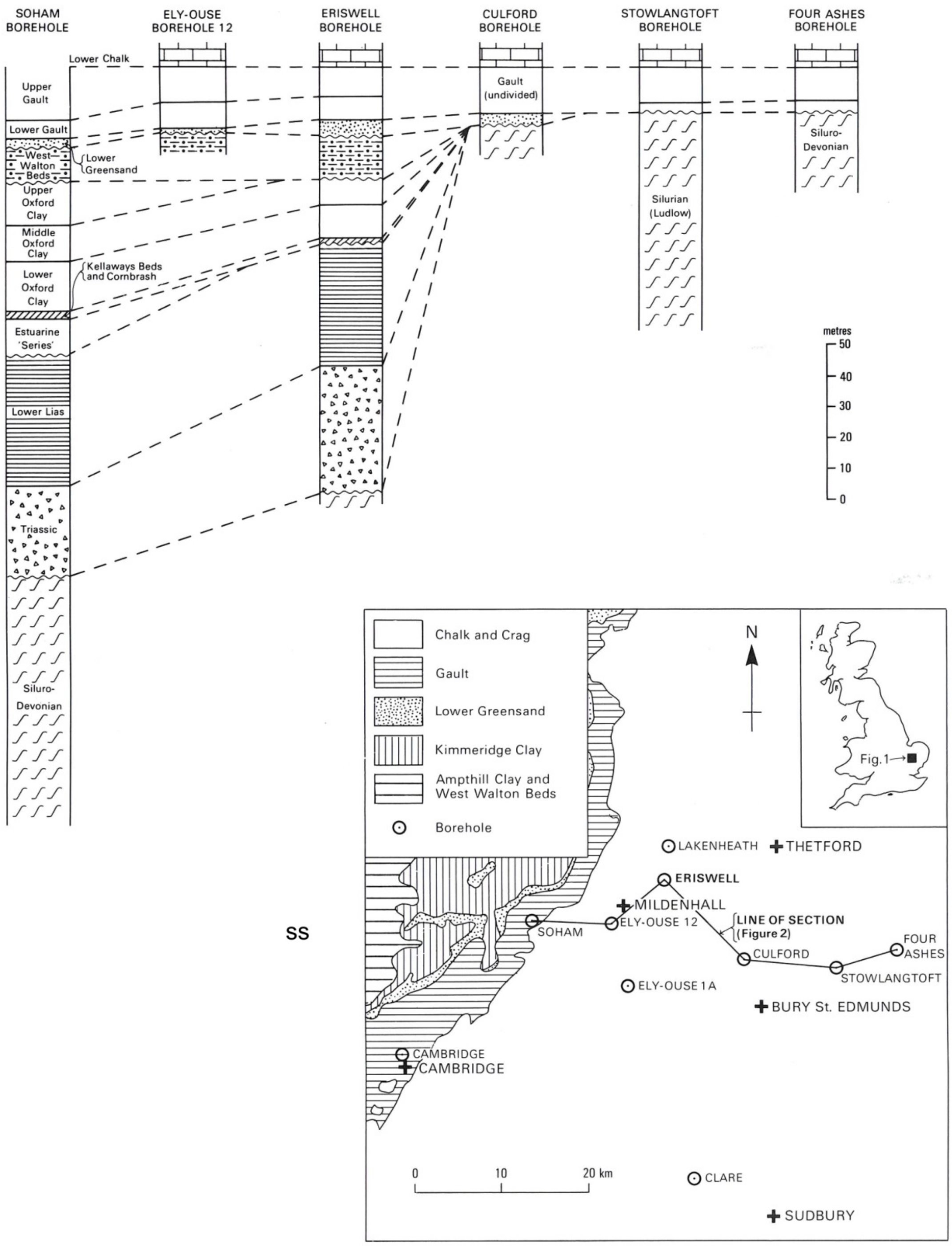


Figure 13 Correlation and thickness variation of Silurian–Cretaceous successions at the south-western margin of the East Anglia region (from Bristow et al., 1989, figs. 1 and 2). British Geological Survey © UKRI 2018

4.2.1.3 Lias Group — LSSR

The Lias Group is a mudstone-dominated succession containing significant amounts of silty mudstone and limestone, the latter typically occurring as thin units interbedded with mudstone. In the East Anglia region its maximum thickness is about 250 m and, with the exception of small areas near Bedford, is almost entirely concealed by younger geological units (Gallois, 1994; Barron, 2015). Thickness data for the group as a whole show that it thins south-eastwards across the East Anglia region (Figure 13 and 14); it is around 150 m thick in the Tydd St Mary Borehole near King's Lynn, about 50 m thick near Ely and Norwich, and largely absent in the subsurface over the region south-east of Cambridge and Norwich (Gallois, 1994; Barron, 2015).

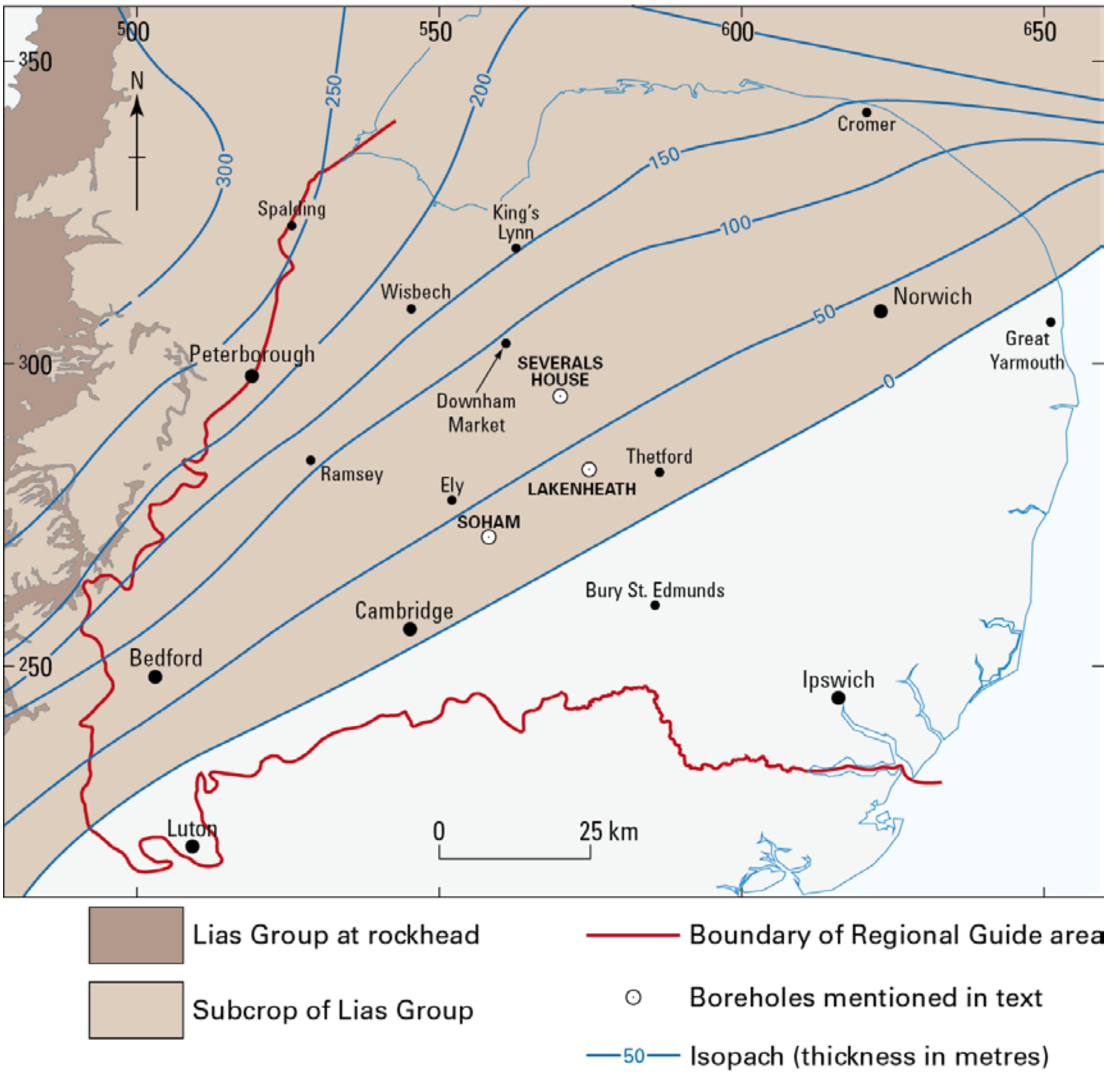


Figure 14 Thickness variation of the Lias Group (from Barron, 2015, fig. 21). British Geological Survey © UKRI 2018

The group comprises five subdivisions in total, although the oldest (Blue Lias/Scunthorpe Mudstone Formation) is not present in East Anglia, and the extent to which the others are developed and can be distinguished across the region, is variable (Figure 11). The subdivisions that are present, from youngest to oldest are: Whitby Mudstone Formation, Marlstone Rock Formation, Dyrham Formation and Charmouth Mudstone Formation. Only the Whitby Mudstone Formation and the Charmouth Mudstone Formation are considered PRTIs and are described below; The Marlstone Rock Formation is a thin, ferruginous limestone whilst the Dyrham Formation is dominated by siltstone (Barron, 2015).

Information about these units is provided by the BGS memoir for King's Lynn (Gallois, 1994); a BGS Research Report on the stratigraphy of the Eriswell Borehole (Bristow et al., 1989), and a synthesis of lithology and thickness data by Barron (2015) in the recently published BGS British Regional Geology guide to East Anglia (Lee et al., 2015).

The Lias Group is within the depth range of interest along the north Norfolk coast, between The Wash in the west and the area around North Walsham in the east. Southwards the extent of the region where the Group is below the depth range of interest shrinks westwards towards the Mundford–Brandon area in south-west Norfolk and north-west Suffolk. As the subcrop of the Lias Group narrows further to the south-west (Figure 13 and 14) most of the succession rises above the depth range of interest, for example, in the Soham and Cambridge boreholes. Where the group is within the depth range of interest across north Norfolk, it is about 230 m thick below The Wash, approximately 190 m thick in the Hunstanton 1 Borehole, approximately 165 m thick in the North Creake Borehole, approximately 110 m thick in the Saxthorpe Borehole, and 85 m thick in the East Ruston Borehole (NGS3D Model). South-westwards, it is 43 m in the Ellingham Borehole and a similar thickness in the Breckles Borehole (NGS3D Model). However, understanding the thickness pattern of component units of the Lias Group within the depth range of interest is prevented by lack of geological model resolution. Additionally, local variations in depositional conditions and/or patterns of erosion across the London–Brabant massif might produce local variations in thickness and lithofacies within the subcrop, especially perhaps at the south-eastern (feather-edge) limits of the component units of the Lias Group.

Whitby Mudstone Formation

This is the only part of the Lias Group present at outcrop (near Podington [SP 93 63]), and there is little information about it that is specific to East Anglia, apart from comprising fossil-bearing mudstone and limestone overlain by 'poorly fossiliferous grey mudstone' (Barron, 2015). The preserved thickness of 20 m or less reflects the influence of later Jurassic erosion (Barron, 2015). The Whitby Mudstone Formation is thought to be the most aerially extensive of the Lias Group units in the subcrop (Barron, 2015; Figure 11) and the south-eastern subcrop extent of the Lias Group (Figure 14) might speculatively be interpreted as the edge of the formation.

Charmouth Mudstone Formation

This unit of variably silty and calcareous mudstone and siltstone with thin beds of bioclastic limestone is by far the thickest unit of the Lias Group. The thick succession in the Tydd St Mary Borehole (see below), near King's Lynn, shows the development of at least nine prominent limestone units, with frequent development of calcareous, pyritic, sideritic and limonitic mudstone horizons. It reaches 150 to 200 m in the north-west of the East Anglia region (for example, 148.21 m in the Tydd St Mary Borehole, near King's Lynn; Gallois, 1994) and perhaps 100 m in north-east Norfolk (where the succession is interpreted with less certainty); southwards it thins to 40 to 50 m in boreholes at Soham, Lakenheath and Severals House near Ely (Barron, 2015), and 22 m at Eriswell (Bristow et al., 1989) where it is capped by an erosion surface. In common with the Lias Group as a whole, the Charmouth Mudstone thins and becomes absent south-eastwards across the East Anglian region (Figure 11).

4.2.1.4 MERCIA MUDSTONE GROUP (HAISBOROUGH GROUP) — LSSR

The Mercia Mudstone Group occurs at depth across parts of northern East Anglia, and offshore in the adjoining Southern North Sea. Away from the coastal fringe of the region, the Group mostly comprises a relatively thin (< 120 m) succession of locally pebbly sandstone, siltstone and mudstone, sometimes with anhydrite. Close to the coast (e.g. Hunstanton 1 Borehole) and offshore, the succession thickens (around 200 to 500 m) and is mainly dominated by siltstone and mudstone with units of anhydrite and halite.

Information about the Mercia Mudstone Group in East Anglia comes from the BGS memoirs for King's Lynn (Gallois, 1994), Ely (Gallois, 1988), Bury St Edmunds (Bristow, 1990); the Sheet Explanation for Wells-next-the-Sea (Moorlock et al., 2008); the BGS Offshore Regional Report for the Southern North Sea (Cameron et al., 1992), and a synthesis of lithological and thickness data by Smith and Thomas (2015) in the recently published British Regional Geology guide for East Anglia (Lee et al., 2015).

Where present at depth across inland parts of the north-western East Anglia region (Figure 15 and 16) (Smith and Thomas, 2015), units that could potentially be considered PRTIs are generally not a dominant component and combined with the succession being variably thin, they have not been identified as a PRTI. For example, in the Wiggenhall 1 Borehole near King's Lynn, the Group is represented by 84.86 m of pebbly sandstone, sandstone and mudstone interbedded with sandstone, and a similar thickness (around 72 m) occurs in the Spalding 1 Borehole just beyond the western margin of the East Anglia region, where the succession comprises mudstone, sandstone and conglomerate, locally with anhydrite. A much thinner succession occurs in the Upwood Borehole, south of Peterborough, where it is represented by 13.62 m of sandstone, siltstone, conglomerate and mudstone. Dramatic thickening of the Mercia Mudstone in the Hunstanton 1 Borehole to nearly 200 m (NGS3D Model) presages the thickening trend seen in the offshore succession. The equivalence of these onshore deposits to the established subdivisions of the Mercia Mudstone Group (Howard et al., 2008) is not known.

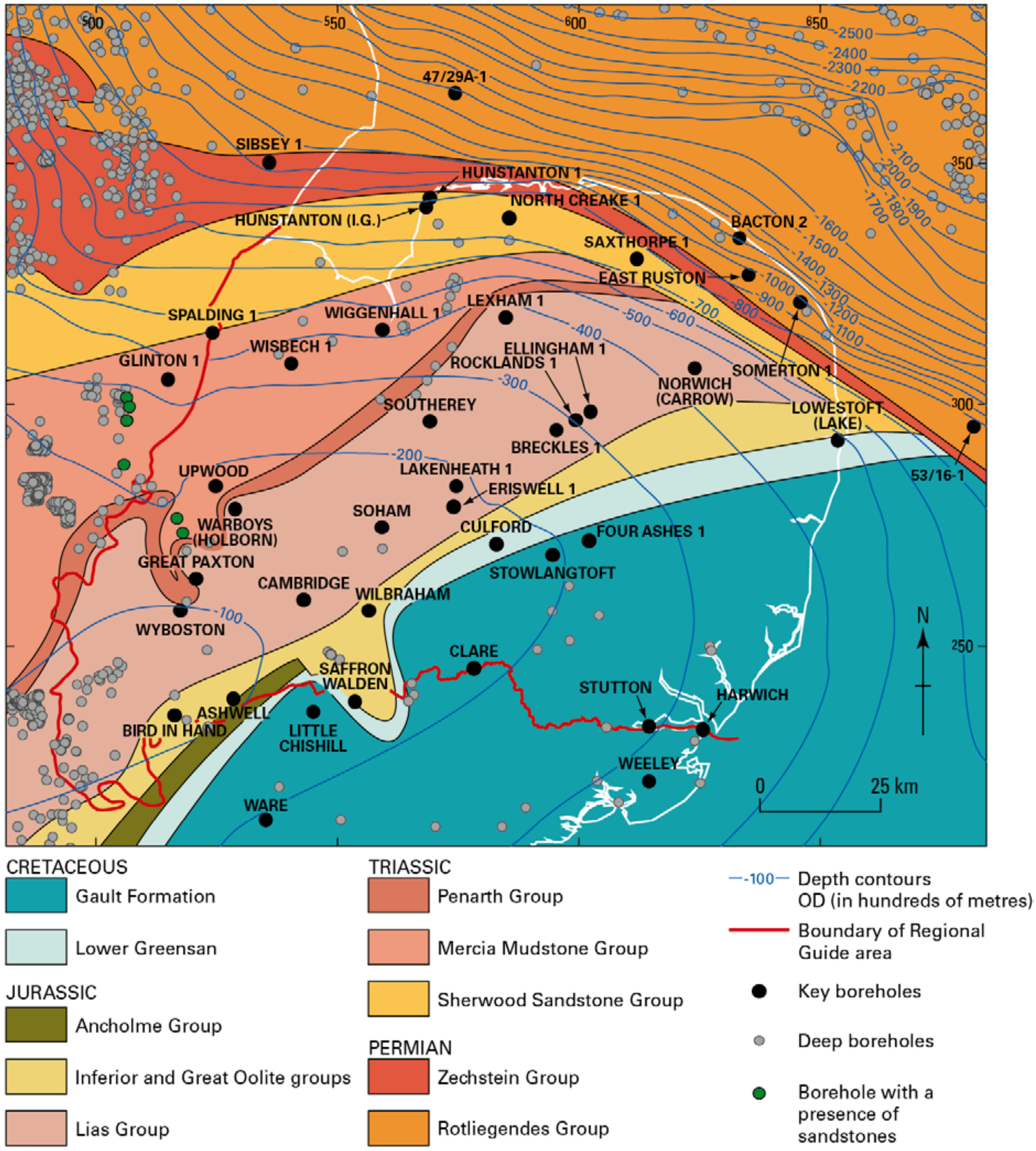


Figure 15 Contour map showing the supercrop of the oldest rocks that overstep the Variscan unconformity, a major erosion surface that separates rocks of late Carboniferous and Permo-Triassic age (from Smith and Thomas, 2015, fig. 19). Note: Lower Greensand Group includes laterally equivalent strata not forming part of this geological subdivision in East Anglia. British Geological Survey © UKRI 2018

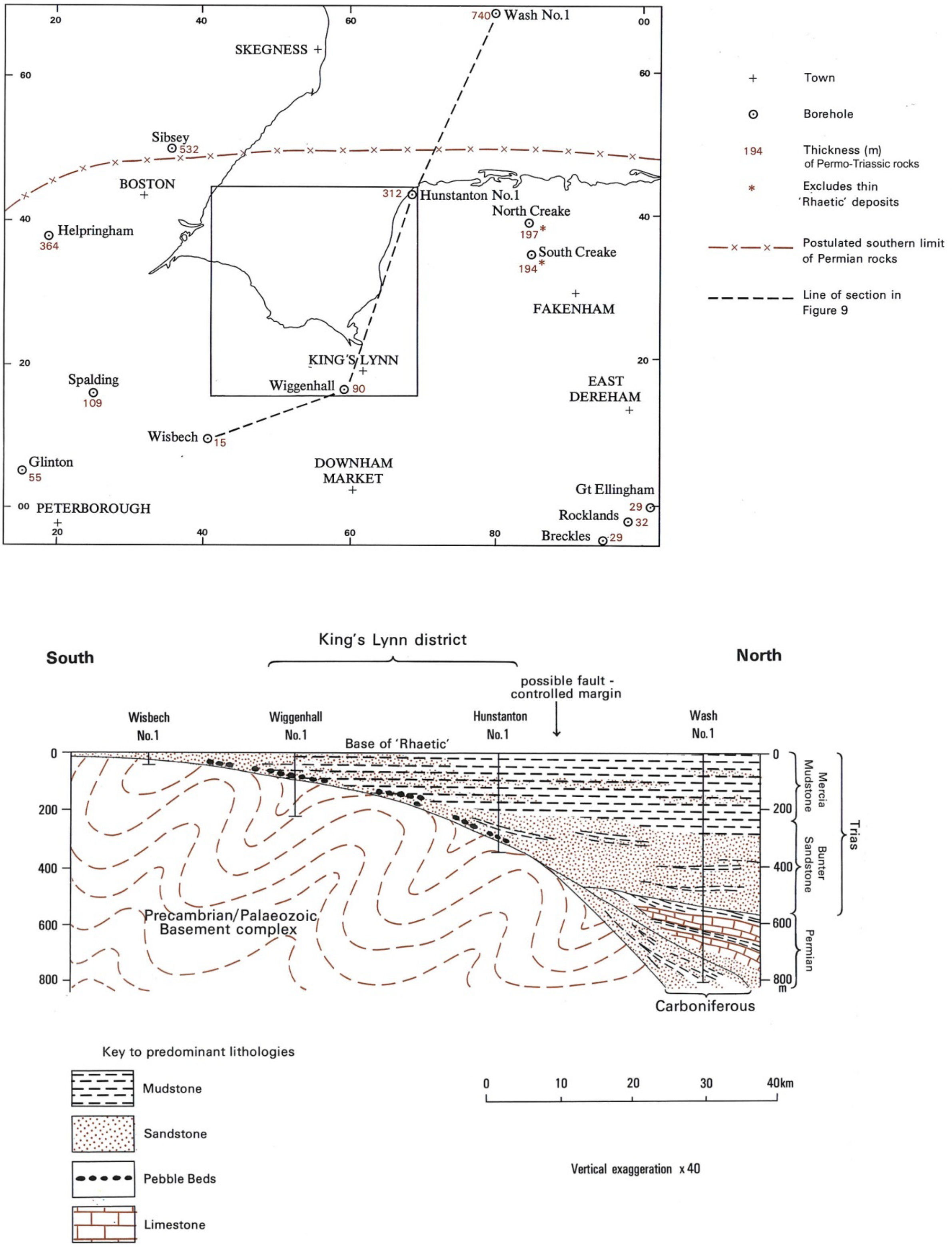


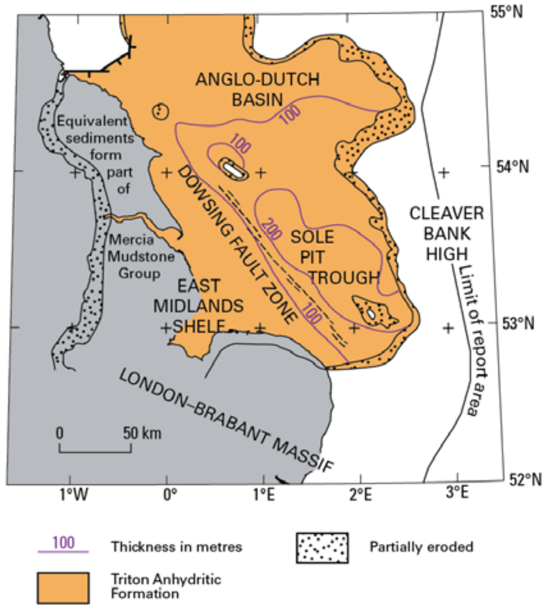
Figure 16 Variation in thickness and character of Permo-Triassic strata in the subsurface of the north Norfolk coast near King's Lynn and The Wash (Gallois, 1994, figs. 8 and 9). British Geological Survey © UKRI 2018

Onshore, the group is within the depth range of interest along the north Norfolk and north-east Norfolk coast, from the latter extending inland south-westwards to near Ely (NGS3D Model). Within this region, the group generally thins south and south-westwards, from just over 100 m across inland parts of north Norfolk (e.g.

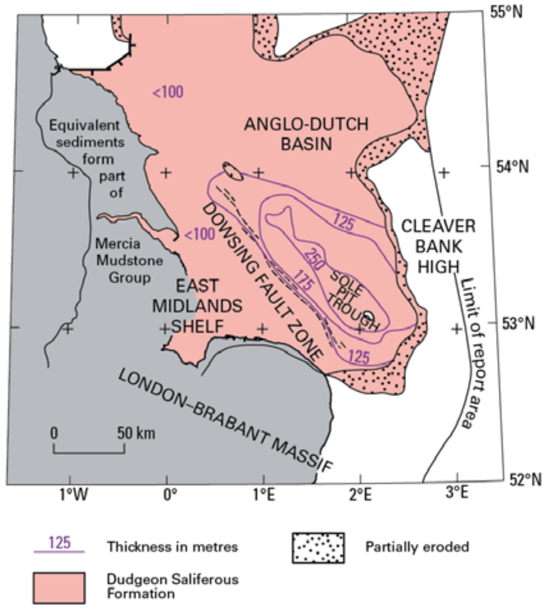
Saxthorpe Borehole), to approximately 70 to 80 m in the Wigenhall and Spalding boreholes at the southern margin of The Wash, and 26 to 28 m in the Breckles and Ellingham boreholes in south Norfolk (NGS3D Model). Further south, the thin and locally preserved Mercia Mudstone Group succession is largely above the depth range of interest, for example in the Upwood Borehole north-west of Cambridge, and the group is absent in the Cambridge Borehole. In north-east Norfolk, the group also thins and eventually pinches out near Wymondham, south-west of Norwich, where Triassic deposits are cut out by Silurian strata (NGS3D Model). This pattern of thinning is probably in response to the palaeogeographical configuration of the London–Brabant massif, influencing patterns of Triassic sedimentation or later erosion.

Much thicker successions representing the Mercia Mudstone Group, largely within the depth range of interest, occur at depth along the northern and eastern coastal fringe and further offshore from the East Anglia region; for example Wash No. 1 Borehole (774.5 to 994.86 m; Figure 16), Bacton 2 (628 to 864 m depth), Somerton 1 (depth 567.3 to 708.64 m) and Aldbrough (south of Hornsea, East Riding of Yorkshire: depth 741–923 m) boreholes, as well as the Hunstanton 1 Borehole (depth 518.2 to 715.4 m; Figure 16) discussed above. In the Southern North Sea, strata equivalent to the Mercia Mudstone Group are more than 500 m thick (for example offshore borehole 52/05-11, between 708 and 1058 m OD; NGS3D Model; Cameron et al., 1992). In the Wash No. 1 Borehole, 112.77 m of silty mudstone with some sandstone interbeds occur above 107.6 m of mudstone, with anhydrite in the lower part and sandstones in the upper part (Gallois, 1994). In the Somerton 1 and Aldbrough boreholes the dominant rock types are mudstone, siltstone and sandstone with horizons of gypsum and anhydrite. In the Southern North Sea this succession was designated the Haisborough Group by Cameron et al. (1992) and is identified as an evaporite PRTI, The Haisborough Group, comprising three formations (in descending order: Triton Anhydritic Formation, Dudgeon Saliferous Formation, Dowsing Dolomitic Formation), is equivalent to the Mercia Mudstone Group of eastern England. Thicknesses are variable in the offshore succession (Figure 17) partly in response to zones of faulting (for example the Dowsing fault zone) (Cameron et al., 1992).

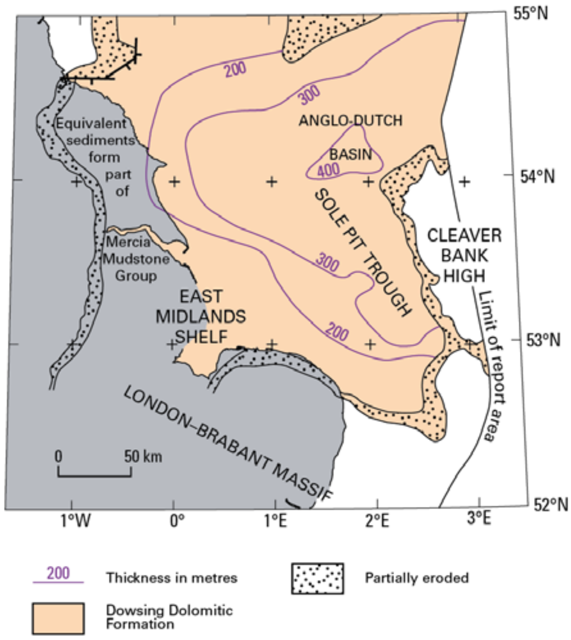
The Triton Anhydritic Formation (Figure 17) comprises a thick succession (up to 250 m) of mudstones with thin layers of anhydrite that locally, in the middle part of the formation, are very frequent and define the Keuper Anhydritic Member (Cameron et al., 1992). Below this, the Dudgeon Saliferous Formation (up to 350 m thick; Figure 17) is a mixture of mudstone, halite and anhydrite, with beds of halite dominating the upper part of the where they form units 1 – 20 m thick and define the Keuper Halite Member (Cameron et al., 1992). In the Dowsing Dolomitic Formation (Figure 17), more than 300 m thick and forming the basal part of the succession, red silty mudstones, dolomite and interbedded halite are predominant, with locally developed sandstone at its base. Three named halite units, usually with thin interbedded mudstone units, are recognised in the Dowsing Dolomitic Formation: the highest Muschelkalk Halite Member extends further south towards the East Anglia region than underlying halite units (Figure 17), and is typically 40 – 60 m thick, with halite 10 – 20 m thick in the central part of the unit (e.g. Borehole 43/20-1; Cameron et al., 1992); the underlying Upper Röt Halite Member only occurs in the northern part of the Anglo-Dutch Basin, and is 5 – 11 m thick, and the lowest Main Röt Halite Member is typically 60 – 80 m thick with five cycles of mudstone, dolomite/anhydrite, halite. The development of the evaporites offshore in the Haisborough Group is mainly outside of the region, with distribution and depth range poorly understood and not modelled as a PRTI within the offshore limits of the East Anglia region. It is the mudstone component that is identified as a PRTI.



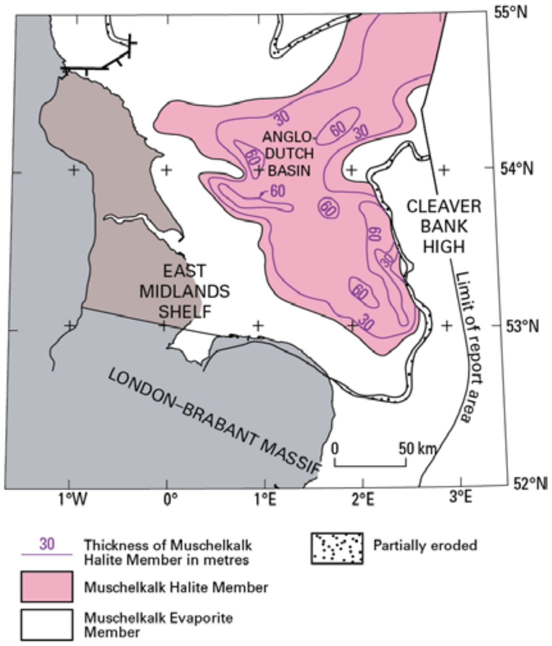
Distribution and thickness of the Triton Anhydritic Formation (Cameron et al., 1994, fig. 61)



Distribution and thickness of the Dudgeon Saliferous Formation (Cameron et al., 1994, fig. 58)



Distribution and thickness of the Dowsing Dolomitic Formation (Cameron et al., 1994, fig. 52)



Distribution and thickness of the Muschelkalk Halite and Muchelkalk Evaporite members (Cameron et al., 1994, fig. 57)

Figure 17 Distribution and thickness of Triassic units in the Southern North Sea. British Geological Survey © UKRI 2018

4.2.1.5 SHERWOOD SANDSTONE GROUP (BACTON GROUP) - LSSR

The Sherwood Sandstone Group has a limited occurrence at depth across the northern part of the East Anglia region (Figure 15), where it is represented in boreholes at North Creake and South Creake. In these boreholes the succession does not include significant PRTIs, comprising sandstone overlain by interbedded sandstones and mudstone (Smith and Thomas, 2015), about 43 m thick in the North Creake Borehole.

In the Southern North Sea the Sherwood Sandstone is equivalent to the Bacton Group of Cameron et al. (1992), where it comprises a sandstone-rich upper part (Bunter Sandstone Formation), underlain by a mudstone-rich lower part (Bunter Shale Formation), in total up to 700 m thick. The Bunter Shale is a PRTI, and although best developed in more offshore regions (Figure 18) it closely approaches the north-east coast of the East Anglia region, and is more than 250 m thick in Borehole 52/5-1 (Cameron et al., 1992).

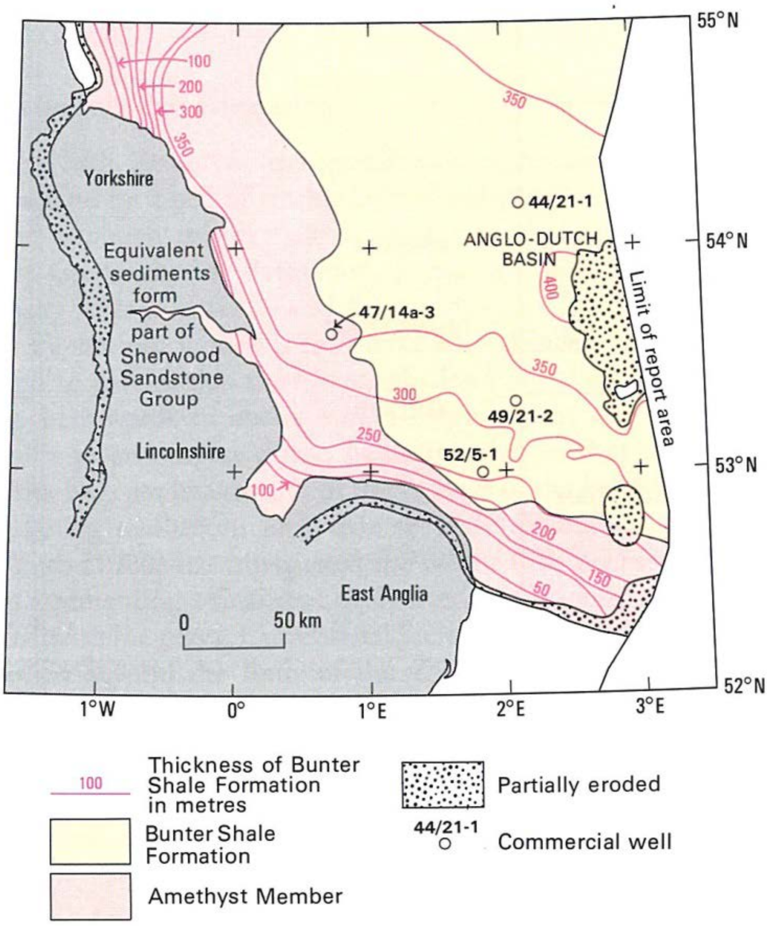


Figure 18 Distribution and thickness of the Bunter Shale Formation and the distribution of the Amethyst Member (from Cameron et al., 1992. Figure 47). British Geological Survey © UKRI 2018

The main information source about the Bunter Shale Formation adjacent to the East Anglia region is the BGS Offshore Regional Report on the Southern North Sea (Cameron et al., 1992). The Formation typically comprises red-brown silty mudstone, with thin siltstone units, and minor dolomite and anhydrite (Figure 18). Close to the northern and north-eastern coast of East Anglia the lower part of the Bacton Group contains frequent thin sandstone units and is designated the Amethyst Member, thickening rapidly offshore from about 50 to more than 200 m (Figure 18). In offshore borehole 52/05-11, strata designated as Sherwood Sandstone are about 130 m thick and entirely below the depth range of interest, but closer to shore, where the Group is just over 100 m thick, borehole data suggests that it rapidly rises above 1000 m depth (NGS3D Model); the lower part of these successions is inferred to contain the equivalent of the Amethyst Member, although precise details are uncertain.

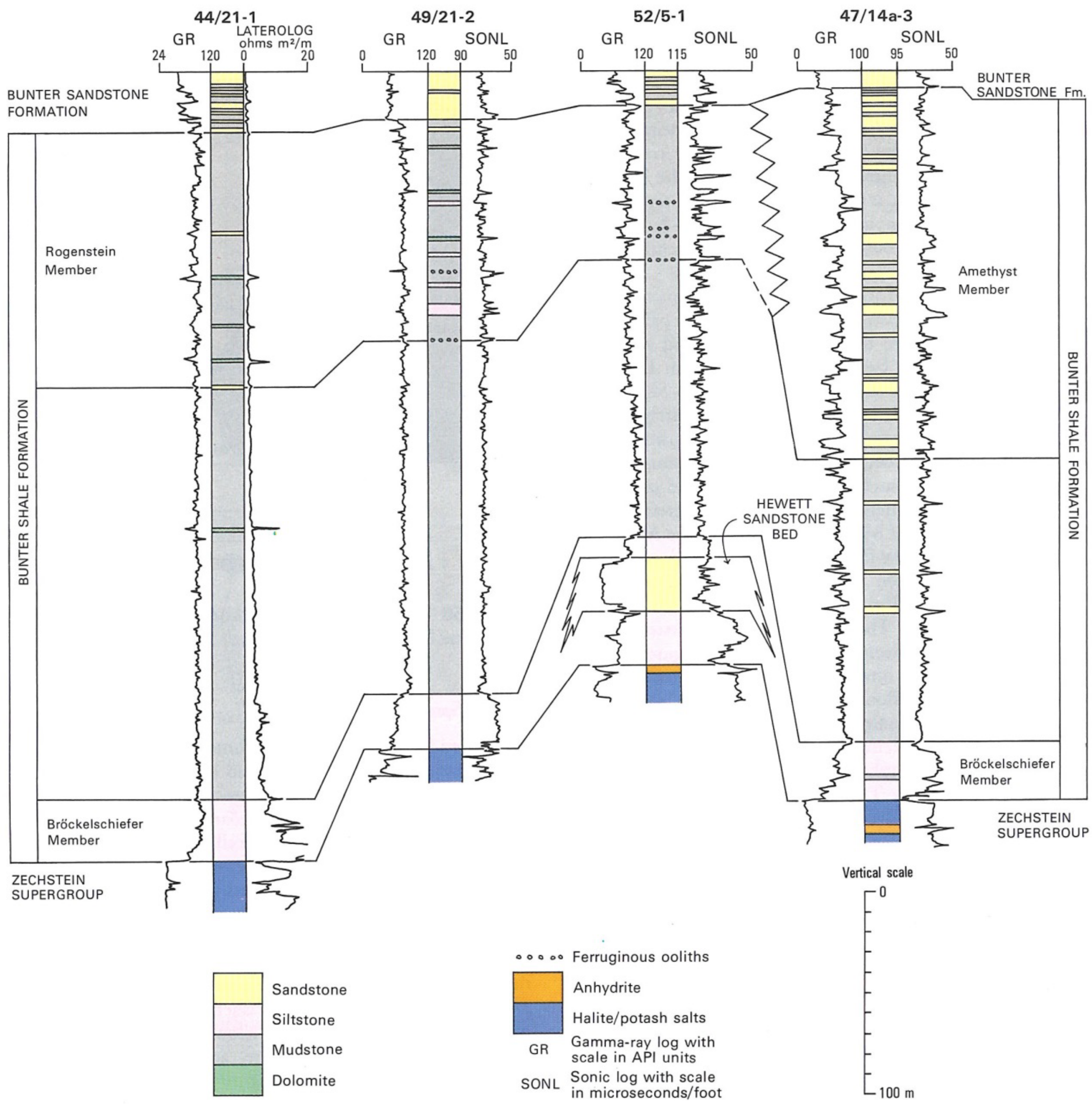


Figure 19 Correlation and rock types in the Bunter Shale Formation in four offshore boreholes (from Cameron et al., 1994, Figure 48). British Geological Survey © UKRI 2018

4.2.2 Older sedimentary rocks

4.2.2.1 WARWICKSHIRE GROUP - LSSR

Carboniferous rocks have limited development beneath the East Anglia region (Smith and Thomas, 2015). Near the east coast, in the Somerton 1 Borehole, the Warwickshire Group and/or Coal Measures Formation strata are about 60 m thick and straddle the lower limit of the depth range of interest. They comprise interbedded units of mudstone (up to 6m thick), siltstone and sandstone. In the nearby East Ruston Borehole, Carboniferous rocks are developed wholly as limestone and are not considered a PRTI. Based on borehole data, Carboniferous sediments are modelled to thin and disappear at depth northwards and southwards along the onshore margin of the East Anglia coast (NGS3D Model). Offshore, Carboniferous rocks are extensively developed in the Southern North Sea adjacent to the East Anglian region, where they include interbedded sandstones, siltstones and mudstone in a succession that is the time-equivalent of the Warwickshire Group, for example in boreholes 52/05-11, 53/12-3 and 53/16-1 (Cameron et al., 1992). In borehole 53/16-1, these rocks occur within the depth range of interest (785 – 896 m; Cameron et al., 1994).

4.2.3 Basement rocks

4.2.3.1 LOWER PALAEOZOIC CRYSTALLINE INTRUSIVE ROCKS - HSR

Crystalline intrusive rocks, of granitic, granodioritic and calc-alkaline composition, are inferred to occur in the subsurface across northern East Anglia and in the vicinity of The Wash (Figure 20 and Figure 21; Smith and Thomas, 2015). Many of these occurrences are thought to relate to a phase of micro-continental collision affecting the East Anglia region during the Ordovician (Smith and Thomas, 2015). Apart from the record of intrusive calc-alkaline rocks in the North Creake Borehole (Smith and Thomas, 2015), none of these crystalline intrusive units appear to have been proved by drilling, and the geophysical data about their presence, extent and depth of occurrence needs to be viewed with caution.

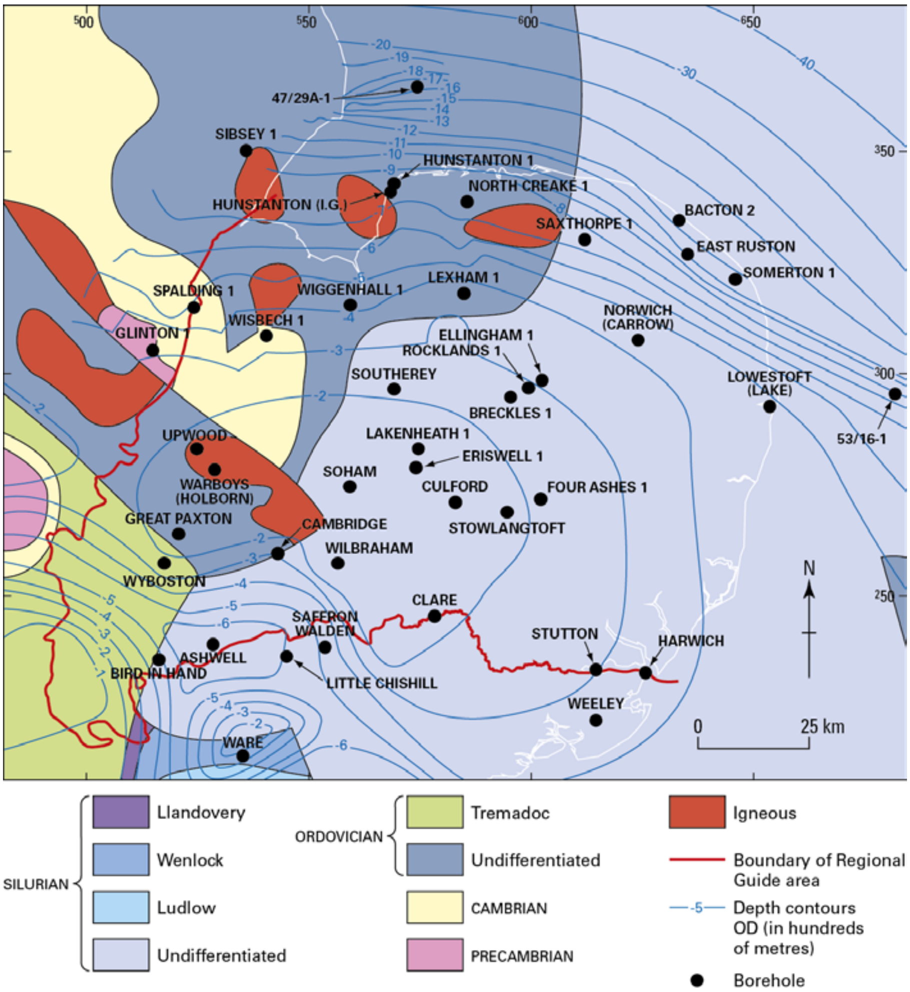


Figure 20 Contour map showing the subcrop of Precambrian and early Palaeozoic rocks beneath the East Anglia region, including inferred crystalline intrusive rocks. The surface of this subcrop is the Acadian unconformity. British Geological Survey © UKRI 2018

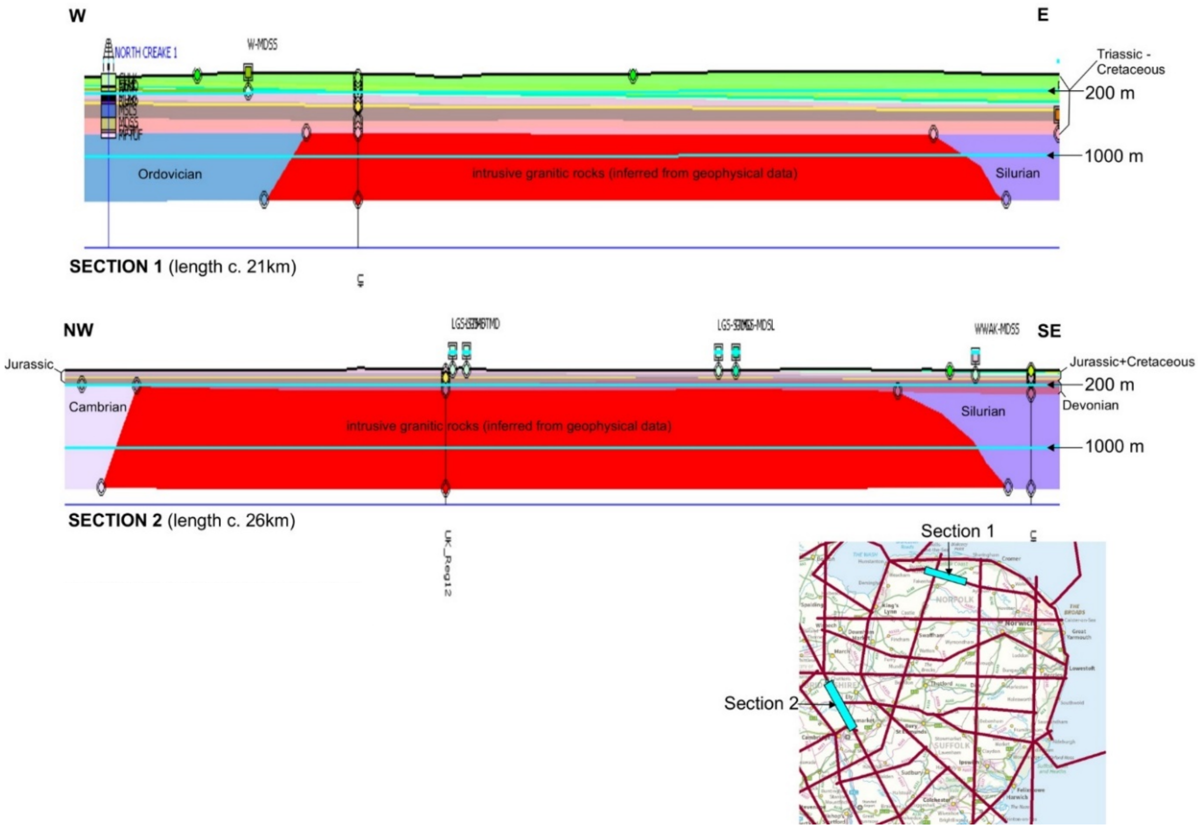


Figure 21 Inferred development of intrusive granitic rocks at depth beneath the East Anglia region. Cross-sections are extracts of the NGS3D model. Contains British Geological Survey digital data © UKRI 2018

Regional gravity data provides the main evidence for these units, described in the BGS memoirs for King's Lynn and The Wash (Gallois, 1994), Bury St Edmunds (Bristow, 1990); BGS Sheet Explanation for Wells-next-the-Sea (Moorlock et al., 2008), Woods and Chacksfield (2012), and a synthesis of geophysical data by Smith and Thomas (2015) in the recently published British Regional Geology guide for East Anglia (Lee et al., 2015).

If present, these igneous intrusions are likely to be associated with an extensive zone of thermal metamorphism where they abut host Palaeozoic (Cambrian–Silurian) rocks, although the character and extent of this is unknown. The presence of a large granitic mass at depth across north Norfolk has been widely accepted (e.g. Mortimore et al., 2001, fig. 1.15), although the regional gravity data on which this feature is based might alternatively be consistent with the presence of two elongated, possibly fault-bounded basins of relatively low-density sedimentary rocks (Woods and Chacksfield, 2012).

All of the inferred occurrences of intrusive igneous rocks are within the depth range of interest, the main developments of these being on the western side of The Wash around Boston; along the eastern side of The Wash, around Heacham; near Tydd St Giles just inland on the southern margin of The Wash; near Thursford in north Norfolk; near Ely and Soham, north and north-east of Cambridge; and near Oundle, south-west of Peterborough (NGS3D Model). Modelling suggests 350 m of these rocks may occur in the lower part of the depth range of interest across north Norfolk (Figure 21), and a similar thickness beneath the east coast of The Wash. In the region immediately south of The Wash, about 600 m of crystalline rocks are modelled to occur within the depth range of interest, and they occupy almost the whole of the 200 to 1000 m depth interval between Ely and Cambridge (Figure 21), although this declines rapidly eastwards as the boundary of the igneous intrusion is crossed (NGS3D Model).

4.2.3.2 Avalonian Proterozoic Crystalline Basement: HSR

No rocks of this age are shown on the NGS3D Model, but they are reported in the Glinton Borehole, near Peterborough, by Smith and Thomas (2015), where they are described as 'felsic ash-flow tuffs with textures characteristic of ignimbrites', dated (U-Pb) as 612 to 616 Ma. The 29.5 m thick succession is present in the borehole between 361 m and 390.5 m (borehole TD), and is therefore within the depth range of interest.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in East Anglia 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 above, are identified.

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

5.2 REGIONAL TECTONIC SETTING

Compared to surrounding regions, the nature of the basement and deep structure of the East Anglia region is very poorly known, and a matter for considerable conjecture (e.g. see Turner, 1949; Pharaoh et al., 1987; Woodcock, 1991; Smith and Thomas, 2015). In part this is a result of a paucity of deep boreholes penetrating the basement of the region. In the north-eastern 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 Triassic, Jurassic, Cretaceous and Cenozoic (younger sedimentary cover). These cover designations are equivalent to the text descriptors 'older sedimentary bedrock' and 'younger sedimentary bedrock' respectively, on the regional summary maps (Figure 3). The limited basement borehole samples available have been interpreted by Pharaoh et al. (1987a) 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, and 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 west-north-west-trending basement grain.

The region lies to the north of the Midlands microcraton (Wills, 1978; Pharaoh et al., 1987; Lee et al., 1990; Smith et al., 2005; Chadwick and Evans, 2005), part of an Avalonian (Neoproterozoic) terrane incorporated into the metamorphic basement of Britain during the Caledonian orogeny. That part of the Avalonian terrane lying to the north of the microcraton experienced extension during early Palaeozoic times, associated with the development of the deep Welsh and Anglian Caledonide basins, the former lying outside the region to the west, the latter inferred to underlie the region. These basins are inferred to have developed at the southern margin of the Iapetus Ocean, and its embayment to the east, the Tornquist Sea. After several phases of subsidence in Cambrian to Silurian times (Molyneux, 1991; Woodcock and Pharaoh, 1993), the basins were inverted during the Acadian phase of the Caledonian orogeny in Early Devonian (about 395 Ma) times, when construction of a new palaeocontinent, 'Laurussia', was completed. Acadian deformation was intense in the former basinal areas, producing strong folding and cleavage development (Soper et al., 1987); it was less intense within the microcraton where cleavage is generally absent. Two basement structures with a north-west trend, referred to as the Glinton and Broadlands thrusts by Pharaoh (2005) are inferred to have formed during this tectonic episode.

Subsequent to the climax of the Caledonian orogeny in the Acadian phase (Early to Mid Devonian), the region was uplifted and underwent erosion. The relatively low-grade metasedimentary rocks of the region were eroded into the foothills of the Caledonian mountain chain. The foothills formed a massif, extending from Wales through London to the Brabant massif of Belgium, referred to as the Wales–London–Brabant massif. Strata of the Devonian and Carboniferous systems (the 'older cover', in the context of the present report) onlap onto the massif, that extends through the region from the East Midlands to The Wash.

In Early Devonian times, the continents of Armorica and other Gondwana-derived terranes collided with Laurussia during the Acadian to Bretonian deformation phases (Ziegler, 1990). 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. These formed part of a basin that extended at least from Ireland, eastwards through northern England, the East Midlands and North Yorkshire into the Southern North Sea basin, in a belt lying to the north of the present region. The evolution of the Carboniferous basin complex in northern England is now much better understood as a result of detailed seismostratigraphical studies of reprocessed high-quality seismic reflection data (Ebdon et al., 1990; Fraser and Gawthorpe, 2003).

Far to the south, progressive closure of the ocean basins within the Armorican terrane assemblage resulted in an east–west-trending mountain chain in central Europe from late Namurian times, the region being located about 400 km north of the contemporary Variscan front. During the Westphalian, pulses of compressional deformation and flexural subsidence began to affect the Variscan foreland, of which the region formed part. By late Westphalian times, northward propagation of the thin-skinned Variscan fold-thrust belt onto the foreland had brought the Variscan front to its final position in southern England, still some way south of the region. The propagation of thrusts, final nappe emplacement and the formation of the Variscan front in southern Britain indicates that the final stages of the Variscan orogenic phase must have involved a significant north–south compressional component (Williams and Chapman, 1986; Corfield et al., 1996).

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. This marked the onset of deposition of the 'younger cover' in Permian times. In Triassic times, west–east extension led to further subsidence, with the UK forming part of a major Triassic graben system extending throughout north-central Europe (Scheck-Wenderoth et al., 2008). The main developing graben systems however lay west (e.g. Worcester Graben) or east (Sole Pit Trough) of the region. In Jurassic times, the region formed part of the relatively buoyant Eastern England platform, and largely escaped the end-Cretaceous inversion that affected the offshore Sole Pit Trough to the east. The developing Alpine orogenic belt propagated westward from the Austro-Carpathian area toward the Alpine Tethys, reaching the western Alps in Late Cretaceous times (Stampfli and Borel, 2002). This convergence induced compressive stresses to the lithosphere of the Alpine foreland, causing inversion of graben structures such as the Sole Pit Trough. In the Cenozoic, the region lay in the Alpine foreland 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 offshore (Glennie and Boegner, 1981; Pharaoh et al., 2010), as well as more widespread, regional uplift.

A more comprehensive account of the structural evolution of the British Isles is presented in Appendix A (Pharaoh and Haslam, 2018)

5.3 MAJOR FAULTS

The major faults selected from analysis of the UK3D model and published maps in the region (Figure 22), exhibit two dominant orientations reflecting the structural history described above. In this region, the younger cover sequence is relatively thin, but thickens to the north-east towards the North Sea basin. Carboniferous rocks of the older cover occupy a restricted area of subcrop adjacent to the coast in north-east Norfolk, where they form an extension of the North Sea Carboniferous basin. Although faulting affects the younger cover in places, the displacements are rather small, of the order of 10 to 50 m at most. The most significant such structure is the Tinwell–Marholm Fault, a west–east-trending fault that extends into the region from the adjacent Central England region. This fault has a northward downthrow affecting Mid Jurassic strata and is inferred by Hains and Horton (1969) to be post-Jurassic in age.

Potentially more significant in the context of this report are two inferred fault zones identified and mapped using seismic reflection data in the comparatively shallow, pre-Permian basement. The Glinton Thrust is a seismically imaged structure (Pharaoh, 2005) within the Neoproterozoic–Palaeozoic basement of the Fens, just east of Peterborough. Analyses of 2D reflection seismic lines allow it to be mapped as a continuous, inclined seismic reflector for a strike width of about 20 km (Chadwick and Evans, 2005) and for about 15 km downdip to the north-east. After depth conversion the structure is inferred to dip to the north-east at about 26°, possibly flattening at depth. The structure is truncated by a thin sequence of Triassic and Jurassic strata of the younger cover about 500 m thick, and does not displace them. Declining signal quality towards the subcrop means that the thrust cannot be followed right up to the unconformity. The older cover sequence is missing in this area, but is present farther north-west, at the eastern end of the Widmerpool Graben (see Central England region report) where the Denton Fault is inferred to represent the prolongation of the Glinton structure to the north-west (Pharaoh et al., 2011). The Denton Fault represents a continuation of the Eakring lineament, which has a long and complex fault history (Chadwick and Evans, 2005). A phase of significant Carboniferous syndepositional growth was followed by Variscan inversion and Triassic extensional reactivation. Unfortunately the Glinton structure lacks this degree of stratigraphical control. It is however comparable in style and geometry to the Broadlands Thrust (see below) and other Caledonian basement structures in adjacent regions (Pharaoh et al., 2011), so a Caledonian age seems most likely for the Glinton Thrust too.

The Broadlands Thrust is a seismically imaged structure (Arthurton et al., 1994; Pharaoh, 2005) within the Silurian age basement (Molyneux, 1991; Woodcock and Pharaoh, 1993) of the Norfolk Broads, west of Great Yarmouth. Analyses of 2D reflection seismic lines allow it to be mapped as a continuous inclined seismic reflector for a strike width exceeding 20 km (Chadwick and Evans, 2005) and for about 14 km downdip with an estimated dip of about 19° to the north-east. The structure is truncated by a thin sequence of Triassic and Cretaceous strata of the younger cover, and does not displace them. Its relationship to the minor Carboniferous basin subcropping to the north-east is unclear (Chadwick and Evans, 2005), but the latter may occur in its hanging-wall. Thus the age of the structure is uncertain, but its seismic character and geometry suggest it has affinities with inferred Caledonian (Acadian) basement thrusts, elsewhere in the region e.g. the Glinton Thrust, and adjacent regions (Pharaoh et al., 2011). Its shallowest subcrop is at about 800 m depth (Chadwick and Evans, 2005).

5.4 FOLDING

On the Eastern England platform, the average regional dip of the younger cover is between 1.25º and 2º to east. The dips in the much more restricted older cover are poorly known, but are unlikely to exceed 10º. The metasedimentary rocks making up the Caledonide basement of the region are inferred to be as deformed as those of the Welsh basin, with penetrative folding, cleavage and, locally, greenschist facies metamorphism (Pharaoh et al., 1987).

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.

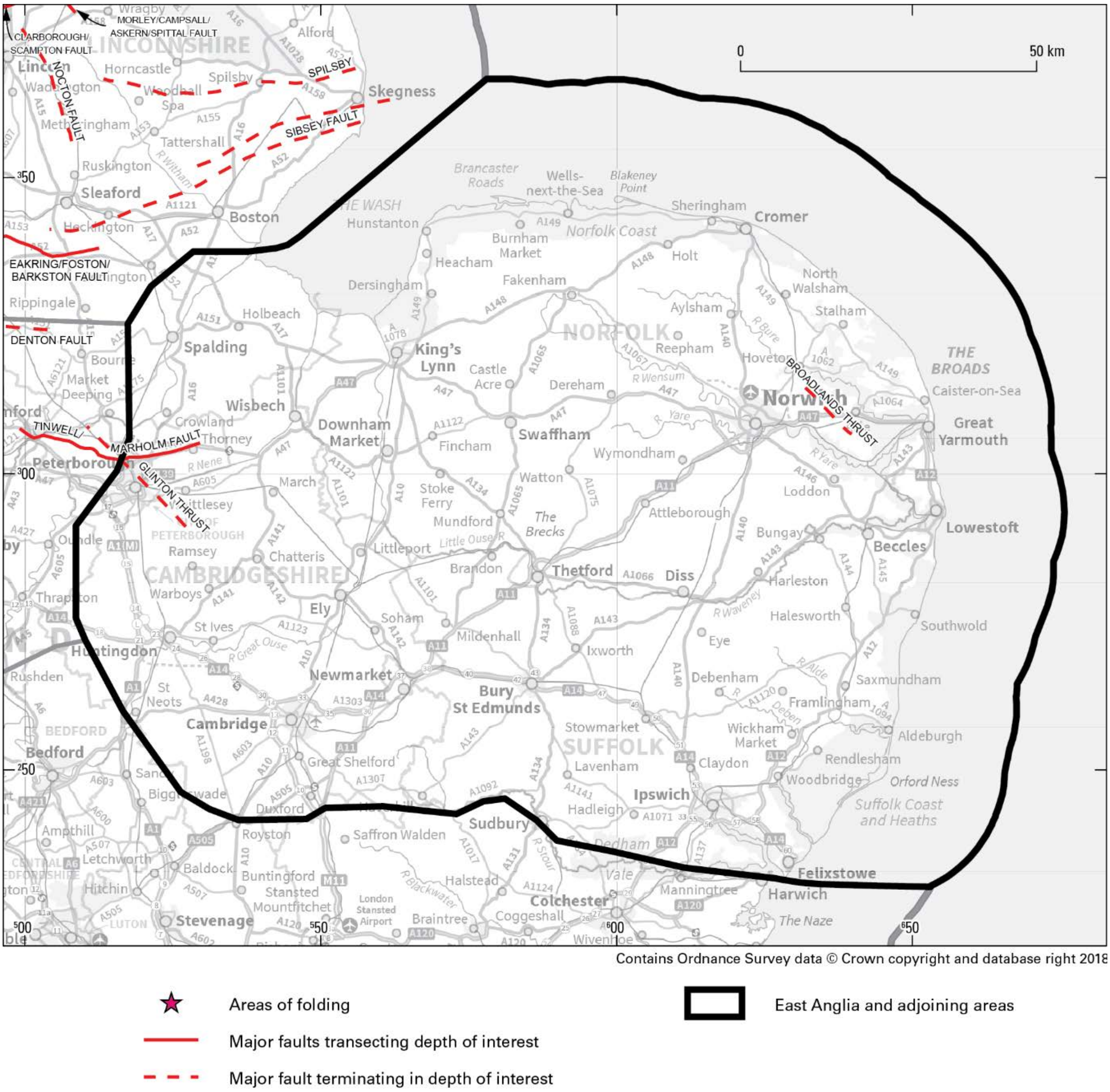


Figure 22 Major faults in the East Anglia region. No areas of folding are identified in the region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290' Contains British Geological Survey digital data © UKRI 2018.

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 East Anglia 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 EAST ANGLIA

There is some available information related to groundwater in the depth range of interest, i.e. between 200 to 1000 m depth. The majority of the available information for the region is related to the relatively shallow groundwater system that is currently exploited for groundwater resources, typically to depths of < 100 m.

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The regional groundwater flow systems in East Anglia are conceptualised as being controlled by the broad distribution of geological units and the regional geological structure; the hydrogeological characteristics of those units; topography and the distribution of recharge; and other hydraulic boundary conditions, such as the coastline of the North Sea to the east of the region and The Wash to the north-west.

The GVS for the East Anglia region (Table 3) divides rock units into younger sedimentary rocks (Quaternary to Permian), older sedimentary rocks (Carboniferous and Devonian) and basement rocks (incorporating igneous intrusions). The structure of the region is relatively simple with the sedimentary cover rocks broadly dipping gently eastwards as described in Chapter 5. The oldest strata to crop out in the region are Jurassic rocks in the west and strata young progressively eastwards. The Jurassic and Cretaceous rocks crop out as roughly parallel bands in an arc which trends south-west to north-east in the southern part to north–south in the northern part. The Palaeogene deposits overlie the Cretaceous Chalk unconformably and the Neogene–Quaternary Crag Group entirely covers the Palaeogene and the eastern part of the Chalk outcrop.

Across the region only the post-Triassic sedimentary cover rocks are exposed and so are subject to direct groundwater recharge. The most permeable units in this part of the cover sequence form the important aquifers in the region, namely the Chalk Group, Inferior Oolite Group (Lincolnshire Limestone Formation) and Crag Group (Powell et al., 2015). Regional-scale groundwater flow in these aquifers, as well as other aquifers in the region, is dominantly down dip towards the east and away from recharge areas in the west. The permeability of the Chalk Group, the most important aquifer in the region, tends to decrease with depth, with the water becoming increasingly saline. Salinity also increases towards the coast. Water supply boreholes mainly use the top 60 m, and hydrochemical evidence suggests that flow at greater depth within the Chalk Group is very limited (Hiscock et al., 1996).

At depth, concealed sedimentary cover rocks of Carboniferous to Triassic age have been proven or inferred, including formations that form principal aquifers in other parts of the UK, such as the Sherwood Sandstone Group, Rotliegendes Group and the Carboniferous Limestone Supergroup. No direct recharge occurs to these units within the sedimentary cover rocks of the region, or the underlying basement rocks and igneous intrusions, and there is no direct evidence for regional-scale hydraulic boundary conditions or regional flow directions for any of these deeper units in the literature reviewed.

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

- a groundwater system in the younger cover sequence of sediments from the Jurassic (Lias Group) to Neogene–Quaternary (Crag Group) — all these sediments are unconfined somewhere within the region and so subject to direct recharge
- a deeper groundwater system consisting of concealed sedimentary cover rocks of Carboniferous to Triassic age, and not subject to direct recharge
- the deepest groundwater system, a relatively low permeability system consisting of basement rocks and igneous intrusions of early Palaeozoic to Devonian age.

The younger cover sequence is hydrogeologically very varied and consists of a sequence of aquifers and aquitards (Powell et al., 2015), where the latter may act to confine underlying aquifers within the groundwater system. However, these relatively low permeability formations are not laterally continuous, thus their potential to confine aquifers within and below the younger cover rock sequence will vary spatially. In addition, many of the predominantly low permeability units within the younger cover sequence contain thin, more permeable strata.

Rocks from all three groundwater systems are found in the depth interval of interest across the region (although the Neogene–Quaternary Crag Group and Palaeogene sediments are all above the interval of interest). Potential pathways for groundwater movement between units within the younger cover sequence are provided by lateral facies changes or overstepping of formations. There are also some potential routes for vertical water movement from geological (e.g. faults) and anthropogenic (e.g. boreholes and mines) features. These potential pathways for groundwater movement between units and groundwater systems are discussed after a description of each of the three broad groundwater systems.

6.3.1 Hydrogeology of the younger cover sequence

6.3.1.1 NEOGENE–QUATERNARY CRAG GROUP

The Neogene-–Quaternary age Crag Group is a principal aquifer but not present within the depth interval of interest. It unconformably overlies formations of the Chalk Group, Lambeth Group and Thames Group, and where it is directly overlain by permeable deposits (such as superficial sands and gravels), or itself directly overlies the Chalk (west of the outcrop of the base of the Palaeogene rocks), they are in hydraulic continuity. In the area where the low permeability Palaeogene rocks intervene between the Crag Group and the Chalk Group, water levels in the Crag Group tend to be higher than the (artesian) piezometric surface in the underlying Chalk (Institute of Geological Sciences, 1981). The Crag Group is mainly used as an aquifer in areas where the Chalk is more deeply buried beneath the Palaeogene strata (Institute of Geological Sciences, 1981).

6.3.1.2 PALAEOGENE SEDIMENTS

No part of the Palaeogene Thames Group extends into the depth interval of interest. The London Clay Formation is predominantly a low permeability unit, hydraulically isolating the Crag Group and White Chalk Subgroup aquifers in the areas where it is present between them. It also locally forms the base to permeable superficial deposits such as glacial sand and gravel (Institute of Geological Sciences, 1981). In this region, the Harwich Formation comprises mainly clayey silt or silty clay (Lee et al., 2015), which are low permeability lithologies. The Lambeth Group consists predominantly of clays and thus forms a low permeability layer (e.g. the Reading Formation and Woolwich Formation are described as aquitards in Powell et al., 2015). The Upnor Formation (at the base of the Lambeth Group) is more variable in lithology, and in the south-west of its outcrop area it typically comprises glauconitic sands (Aldiss, 2015). Small quantities of water may be present in the more permeable horizons, forming minor perched aquifers, with some groundwater flow if these horizons have recharge and discharge zones. No part of the Lambeth Group extends into the depth interval of interest (below 200 m) in NGS3D. The Thanet Formation and Ormesby Clay Member comprise mainly low permeability clay-rich lithologies, although locally the Thanet Formation may provide important water supplies. Neither the Thanet Formation nor the Ormesby Clay Member extend into the depth interval of interest (below 200 m) in NGS3D.

6.3.1.3 THE CHALK AQUIFER

The White Chalk Subgroup, a principal aquifer, (the upper, younger, part of the Chalk Group) is the most significant aquifer for water supply in the region, and produces the highest yields (Powell et al., 2015). The Chalk Group comprises the White Chalk Subgroup and the underlying Grey Chalk Subgroup. The Grey Chalk Subgroup contains a higher proportion of finer-grained material (marl) than the White Chalk and thus the aquifer properties are typically considered as poor (Allen et al., 1997). However, there is some evidence that this is not the case in East Anglia.

Recharge occurs mainly where the White Chalk is exposed at outcrop and via drainage through overlying permeable deposits (i.e. glacial sands and gravels, Crag Group, Lambeth Group, Thanet Formation) where they are present and in hydraulic continuity. These overlying deposits can provide significant additional storage to the Chalk aquifer (Allen et al., 1997). Where glacial till overlies the White Chalk aquifer it may reduce recharge in those areas, and even confine the aquifer (Allen et al., 1997)**.**

Deep buried channels (tunnel valleys), filled with superficial deposits, have been identified in East Anglia (Lee et al., 2015) and may inhibit groundwater flow in the Chalk (Pattison et al., 1993). Bristow (1990) also considers that the buried channels may enable increased infiltration to the Chalk and thus increase the permeability by solution enhancement of fractures.

Where present, the low permeability Palaeogene strata confine the Chalk Group aquifer. For example, in the Lowestoft and Saxmundham district, the potentiometric surface of the confined Chalk aquifer is generally within the overlying Palaeogene deposits, and around Halesworth (where the Chalk Group is confined by Palaeogene strata) artesian conditions have been recorded (Moorlock et al., 2000). The Palaeogene strata also limit vertical groundwater movement where they intervene between the Crag Group and the White Chalk.

Karst features are present in the Chalk Group of the region (Waltham et al., 1996) and may provide a route for surface water to enter the Chalk aquifer in an area where recharge is otherwise limited by the thick, generally low permeability glacial till. However, there is no evidence that these features link to any deeper karst (other than the normal solution-enhanced fractures typically seen in relatively shallow Chalk).

The Chalk Group lies conformably above Early Cretaceous rocks: the Gault Formation and, in North Norfolk, the Hunstanton Formation. The Gault Formation forms a low permeability base to the chalk aquifer (Allen et al., 1997).

Regional groundwater levels have been mapped for the Chalk Group (Institute of Geological Sciences, 1976, 1981), and typically reflect surface topography in a subdued form as well as reflecting the location of base levels controlled by The Wash and the North Sea (Powell et al., 2015). The greatest depth to water in the Chalk is under areas of higher ground (Powell et al., 2015) and regional flow paths in the Chalk tend to be from higher ground (where most recharge occurs) towards valleys and the coast.

The baseline groundwater chemistry the Chalk Group aquifer of East Anglia is controlled by dissolution of the calcite matrix. Till deposits, where present, influence the underlying Chalk Group groundwater chemistry, with relatively older and more mineralised water in the Chalk Group beneath glacial till, while modern recharge is focused at the edges of the till (Ander et al., 2004; 2006).

The hydraulic conductivity of the Chalk Group aquifer results from the presence of an interconnected system of fractures (Allen et al., 1997). Groundwater flow is concentrated along solution-enhanced fractures, which tend to be in the top few tens of metres of the Chalk Group. Allen et al. (1997) notes that only a few fractures may provide the bulk of the transmissivity of the aquifer. Hardgrounds, where present at depths of less than about 100 m, are believed to fracture more cleanly than other parts of the succession and thus can form higher permeability horizons (Allen et al., 1997). Permeability is commonly higher in valleys than in interfluve areas (Allen et al., 1997) and can vary significantly over a small distances (Allen et al., 1997). Allen et al. (1997) reports that many of the most transmissive boreholes in the Chalk Group of East Anglia are (unusually) in the lower parts of the Chalk Group succession; they consider that this could be explained by the presence of the Totternhoe Stone (a more cemented, sandy chalk interval, similar in hydrogeological characteristics to a hardground) and the Melbourn Rock hardground. In the Great Yarmouth district, water abstraction boreholes in the Chalk become less frequent towards the east, where the Chalk Group is present at increasing depth (Artherton et al., 1994) and quality declines due to increasing salinity (Institute of Geological Sciences, 1976). Artherton et al. (1994) reports that the most easterly abstraction is that at Lacon's Brewery in Great Yarmouth, where the top of the Chalk Group lies at 155 m below OD. Allen et al. (1997) states that the most important flow horizons are concentrated near the top of the Chalk Group, with little flow deeper than 50 m below groundwater levels (or below the top of the Chalk Group where confined) (Allen et al., 1997). Geophysical logging of boreholes for the Great Ouse groundwater scheme in East Anglia found that 90 per cent of inflow to the boreholes was in the top 60 m of the aquifer, and the majority of this was in the top 30 m (Allen et al., 1997).

In a study of interstitial water from the Trunch Borehole in Norfolk, Bath and Edmunds (1981) found that samples from 442.3 m bgl, in strata comparing closely with the lower part of the Burnham Chalk in Lincolnshire and Yorkshire (= lower Lewes Nodular Chalk of southern England), and in deeper samples from the Chalk Group, had salinities very similar to that of seawater (Bath and Edmunds, 1981). These samples were identified as connate water subsequently modified by diagenetic reactions (Bath and Edmunds, 1981). The presence of this water from the time of the deposition of the rocks indicates that little or no flushing has occurred through groundwater flow to these depths; in fact the water has been modified geochemically by a single diffusion process within the last three million years (Edmunds et al., 1992). A study of the hydrochemistry and stable isotope composition of the Chalk Group aquifer of north Norfolk by Hiscock et al. (1996) found a transition, at approximately 50 m below sea level, between a shallower region of fresh water (chloride ion concentration mainly <100 mg l^{-1}) and a deeper part with higher chloride concentrations. This equated to an effective thickness of the Chalk Group aquifer (depth of the aquifer beneath the upper surface of the Chalk Group) in their study area of at most 50 to 60 m, and where the Chalk Group was more deeply buried beneath Palaeogene deposits, some 25 m thick (Hiscock et al., 1996). Hiscock et al. (1996) postulate that major flow occurs in near-valley environments, while minor flow takes place beneath interfluve areas to a depth of some 50 to 60 m below the top of the Chalk Group, and suggested that little or no active flow occurs in the Chalk Group beneath that depth.

6.3.1.4 Early Cretaceous Gault Formation and Lower Greensand Group (and laterally equivalent units)

Based on the references reviewed, there is very little information regarding the hydrogeological characteristics of the Early Cretaceous units in the region and none in the depth interval of interest.

The Gault Formation consists mainly of mudstone (Woods, 2015). The low permeability of this formation is proven by it causing confinement of the underlying Carstone Formation (Institute of Geological Sciences, 1976). The Gault Formation is only present in the depth interval of interest in the south-east of the region, in the area south and east of Thetford. It is absent in the north of the area, where its period of deposition is represented by the condensed ferruginous chalky limestone facies of the Hunstanton Formation; there is a transition between the two (Lee et al., 2015). Dissolution of carbonate minerals within the Hunstanton Formation along bedding planes where flow has been focused, forming karst features, has been observed at the coast (Lee et al., 2015).

The Early Cretaceous Lower Greensand Group in this region is represented by the Woburn Sands Formation. The Carstone Formation, postdating the Woburn Sands Formation but laterally equivalent to part of the Lower Greensand Group elsewhere, is present in northern East Anglia but is considered to be of little value as an aquifer (Allen et al., 1997). The Woburn Sands Formation forms an aquifer in the Cambridge–Bedfordshire region, being particularly valuable as a water resource in locations west of the White Chalk outcrop (Institute of Geological Sciences, 1981). The formation dips gently to the south-east (Allen et al., 1997). The aquifer is overlain by the low permeability Gault Formation that confines it and creates artesian conditions in boreholes (Monkhouse, 1974; Allen et al., 1997). Artesian conditions have also been observed in parts of the outcrop covered in low permeability glacial till (Monkhouse, 1974). The Woburn Sands Formation is used for water supply both at outcrop and in the confined zone to a distance of about 15 km (Monkhouse, 1974). Groundwater flow in the aquifer is almost entirely intergranular (Moorlock et al., 2002). The transmissivity was found to vary spatially, and also to reduce significantly when further than 2 km from outcrop; the latter was considered likely to result from generally thinner and more cemented strata at the more deeply confined sites (Allen et al., 1997). In the Cambridge area, groundwater flows from the recharge area at outcrop (to the north-west of Cambridge, where the Lower Greensand Group is overlain by glacial till) to the south-east towards Cambridge (Monkhouse, 1974).

6.3.1.5 Late Jurassic – Early Cretaceous Sandringham Sand Formation

The Sandringham Sand Formation is of Late Jurassic to Early Cretaceous age and is characterised by Powell et al. (2015) as a granular aquifer, stating that the sands offer low yields of poor quality (with elevated iron and chloride), however, well-designed wells can provide supplies of local importance.

6.3.1.6 Ancholme Group

The lithologically variable Jurassic Ancholme Group contains a variety of aquifers and aquitards (Powell et al., 2015). However, based on the references reviewed, there is very little information regarding the hydrogeological characteristics of the units within the group across the region and none in the depth interval of interest.

The Kimmeridge Clay Formation and the underlying Ampthill Clay Formation are mudstones and are defined as aquitards by Powell et al. (2015), being composed of low permeability deposits. The West Walton Formation comprises alternating beds of carbonaceous silty mudstone and calcareous mudstone, with some limestone beds. The limestones can yield small but useful supplies in some areas, e.g. around Upware (British Geological Survey, 1984), and Powell et al. (2015) classify them as a fractured aquifer. However, the water quality is typically poor with high chloride ion concentrations where overlain by clays (Institute of Geological Sciences, 1981).

The Oxford Clay Formation predominantly comprises mudstone, and is classified as an aquitard by Powell et al. (2015), and may confine underlying aquifers (Edmonds and Dinham, 1965). The underlying Kellaways Formation consists of the upper Kellaways Sand Member (fine-grained sandstone and sandy siltstone, interbedded with silty mudstone) and the lower Kellaways Clay Member (laminated silty mudstone beds) (Barron et al., 2015). Due to the relatively permeable nature of the Kellaways Sand Member, the formation is classed as an aquifer by Powell et al. (2015).

6.3.1.7 Great and Inferior Oolite groups

There is very little information regarding the hydrogeological characteristics of the units within the Great and Inferior Oolite groups across the region, based on the references reviewed, and none in the depth interval of interest.

The Great Oolite Group is of highly variable composition, predominantly limestones and mudstones. It crops out to the west of Peterborough. The formations that make up the Great Oolite Group have contrasting permeabilities due to their different lithological compositions. Powell et al. (2015) classify the Cornbrash and Blisworth Limestone formations as aquifers, while the Rutland Formation is a relatively low permeability unit and acts as a confining bed (Horton, 1989).

The Inferior Oolite Group consists of: the Lincolnshire Limestone Formation (oolitic limestone); the Grantham Formation (sands, silts, silty clays and mudstones) and the Northampton Sand Formation (mainly silty and sandy limestones) (Horton, 1989). The Lincolnshire Limestone Formation is a principal aquifer (Allen et al., 1997) and within the region is the most important source of groundwater in the Peterborough area (Horton, 1989). The Lincolnshire Limestone Formation is extremely permeable in the depth interval of active groundwater exploitation, owing to the presence of solution-enhanced fractures (Horton, 1989). The Lincolnshire Limestone Formation is confined by the overlying Rutland Formation and boreholes in some parts of the confined aquifer overflow at the surface (Horton, 1989). The chemistry of the water in the Lincolnshire Limestone Formation changes from the outcrop area into the confined area. In the outcrop area the water chemistry is dominated by calcium and bicarbonate ions, with lesser magnesium and sulphate ion concentrations, and the water is hard. The water further down dip is softer as a result of ion exchange (Horton, 1989).

6.3.1.8 LIAS GROUP

There is almost no information regarding the hydrogeological characteristics of the units within the Lias Group across the region, based on the references reviewed, and none in the depth interval of interest. The Lias Group comprises mudstone, siltstone, limestone and sandstone. The thick Charmouth Mudstone Formation is the dominant stratum within the Lias Group, and is composed of low permeability material. The Marlstone Rock and Dyrham formations form minor aquifers (Jones et al., 2000).

6.3.2 Hydrogeology of the concealed sedimentary cover rocks of Carboniferous to Triassic age

6.3.2.1 MERCIA MUDSTONE GROUP

The Mercia Mudstone Group is present at depth across the north-west part of the region, where it is of variable thickness. At, and close to, outcrop in other regions, the Mercia Mudstone Group forms a significant aquitard, confining groundwater in the underlying Permo-Triassic sandstone aquifer (e.g. Allen et al., 1997), although some water is obtained from the subordinate dolomitic siltstone horizons (e.g. Arden Sandstone). No evidence regarding the hydrogeological aspects of the Arden Sandstone Formation in this region has been identified from the references cited.

6.3.2.2 SHERWOOD SANDSTONE GROUP

The Sherwood Sandstone Group is present beneath a limited area of the northern part of the region. The Sherwood Sandstone Group forms a principal aquifer, the second most important in the UK, where at or close to outcrop (Allen et al., 1997, page 157). Downing and Gray (1986) describes the hydrogeological potential of the Sherwood Sandstone Group in the East Yorkshire and Lincolnshire basin, a basin in the neighbouring region to the north of East Anglian region. They state that potable waters are found in the Sherwood Sandstone Group for some 15 to 25 km down gradient from the outcrop, but further east the quality deteriorates, and eventually becomes saline (Downing and Gray, 1986,). However, in the East Anglia region the rocks are at considerable depth and a great distance from outcrop. There is no information about their aquifer properties in this area. The Sherwood Sandstone Group is not considered a principal aquifer in this region, but is in other parts of the UK where it is present at shallower depths. The lower part of the Sherwood Sandstone Group has a mudstone-rich lower part, the Bunter Shale Formation. No evidence regarding the hydrogeological aspects of this formation in this region has been identified from the references cited.

6.3.2.3 ZECHSTEIN AND ROTLIEGENDES GROUPS

There is no evidence regarding the hydrogeological aspects of either the Zechstein Group or Rotliegendes Group in the region in the references cited.

6.3.2.4 CARBONIFEROUS SEDIMENTARY ROCKS

The Carboniferous Warwickshire Group rocks at depth in this region are of variable lithology. At Somerton the Warwickshire Group is present and consists of interbedded mudstone, siltstone and sandstone, whilst at East Ruston the sequence is all limestone. No evidence regarding the hydrogeological aspects of this formation in this region has been identified from the references cited.

The Carboniferous Limestone Supergroup forms a principal aquifer in some areas of the UK, but Allen et al. (1997) states that it is not considered to be a major aquifer except in the Mendips, South Wales and the Peak District: these are areas where it crops out. The matrix porosity and permeability of the Carboniferous Limestone is very low, and any significant permeability results from the presence of solution-enhanced fractures (Allen et al., 1997) that form a karstic aquifer. No evidence regarding the aquifer properties of the limestone, e.g. the presence or absence of solution-enhanced fractures, has been identified for this region in the references cited.

6.3.3 Hydrogeology of the basement rocks and igneous intrusions of early Palaeozoic to Devonian age

There are a variety of basement rocks and igneous intrusions of early Palaeozoic to Devonian age present at depth in the region, including: intrusive igneous granite; Devonian and early Palaeozoic rocks, and Avalonian basement rocks. However, no evidence regarding the hydrogeological aspects of any of these formations in this region has been identified from the reviewed literature.

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 (≥15ºC) in the region. Unusually high temperatures at relatively shallow depths are reported from four locations in the area of Chatteris (Cambridgeshire) by Whitaker et al. (1893). For example, a water temperature of 21.9ºC was measured in groundwater from a 4.3 m-deep well (in gravel) at Langwood Hill farmyard. The groundwater temperature in a well sited four miles east of Chatteris was found to be 20.6ºC; at the time of sampling there was ice on nearby ditches and the air temperature was 3.9ºC. In this case the warm water was obtained from a depth of about 2.4–3.0 m bgl, from a sand that was overlain by a thin clay, in turn overlain by peat. These anomalous temperatures are not believed to result from deep flow; it is possible that they resulted from nearby decomposition of organic matter or other chemical reactions. However, this has not been proven (Whitaker et al., 1893).

Across the region, different units come into contact with each other due to overstepping of strata deposited above unconformities. This overstepping means a permeable unit can overlie alternating low and high permeability units: where two permeable units are in direct contact they are likely to be in hydraulic continuity. For example, the Lower Greensand Group rests unconformably on Jurassic and Cretaceous rocks throughout East Anglia, overstepping units of different ages and hydrogeological properties. In addition, contemporaneous deposition of different lithologies can mean lateral changes between rocks with contrasting hydrogeological properties, e.g. the Hunstanton Formation and Gault Formation. However, in both these cases there is no evidence for regionally significant effects on the groundwater systems.

Faults can affect the hydrogeology of an area by bringing offset strata into contact. This may position a permeable unit against a lower permeability unit, or two different permeable units adjacent to each other. In addition, faults also have their own hydraulic properties: they can form higher permeability pathways between strata, or contain lower permeability deposits which act as a barrier to flows within permeable units. Notwithstanding these generic observations, no evidence for the presence of faults affecting the hydrogeology of this region has been found in the references cited.

6.4.2 Anthropogenic pathways

There are a number of deep boreholes in this region, mainly drilled for hydrocarbon exploration or research. If these were not fully sealed (either completely backfilled with low permeability material or, if still in use, casing grouted effectively) they could form pathways for vertical flows between permeable units which would otherwise be hydraulically separated by intervening low permeability units. Seven areas (1 km^2) with more than one borehole >200 m deep have been identified in this region (see Chapter 8), but there is no evidence in the references cited that these deep boreholes affect the hydrogeology of the region or act as pathways for rapid flow between relatively deep and shallow groundwater systems. There are no areas in this region with metal mines, coal mines or evaporate mining over 100 m deep.

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

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

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

7.2 GLACIATION

7.2.1 A UK-scale context

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

It is clear from the recent geological record that glaciers have been repeatedly active within the UK landscape over the past two and half million years (Clark et al., 2004; Lee et al., 2011). Numerous periods of glaciation have been recognised, although the scale and extent of glaciers have varied considerably. Most glaciations have been comparatively small (i.e. highland glaciations), although some have been more extensive with glaciers expanding into lowland parts of the UK, i.e. lowland glaciations (Clark et al., 2004; Lee et al., 2011). Over the past half a million years, at least two continental-scale glaciations have affected the UK with ice sheets covering parts of lowland UK, on one occasion as far south as the London area (Figure 20; RWM 2016a; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next one million years is open to conjecture (Loutre and Berger, 2000). This is because the impacts of global warming and the current melting of the Greenland Ice Sheet on the long-term climate system are poorly understood, although the general scientific consensus is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions means that their occurrence cannot be discounted.

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

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

7.2.2 A regional perspective

East Anglia has only been glaciated directly during large continental-scale glaciations over the past 2.588 million years (Quaternary Period: Figure 23; RWM 2016b, Lee et al., 2015). It has not been affected directly by either highland or lowland scale glaciation and this is likely to remain the case in the future (RWM 2016b). Based upon geological evidence and the premise that the recent geological record provides a worst-case analogue for the future, the region may infrequently undergo periods of continental-scale glaciation over the next million years (RWM, 2016b). Important natural processes that may affect the depth range of interest include the incision of tunnel valleys by fast-flowing meltwater streams that occur beneath the glacier and may produce localised erosion over several phases of glaciation to depths beyond 200 m (RWM, 2016b). The region may also be affected by isostatic rebound and/or a glacier forebulge relating to the glaciation of an adjacent onshore (e.g. Eastern England) or offshore region (e.g. North Sea). This may result in increased fracturing and fault reactivation within the subsurface leading to enhanced seismicity (RWM, 2016b). The extensive coastline of East Anglia 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 (RWM, 2016b).

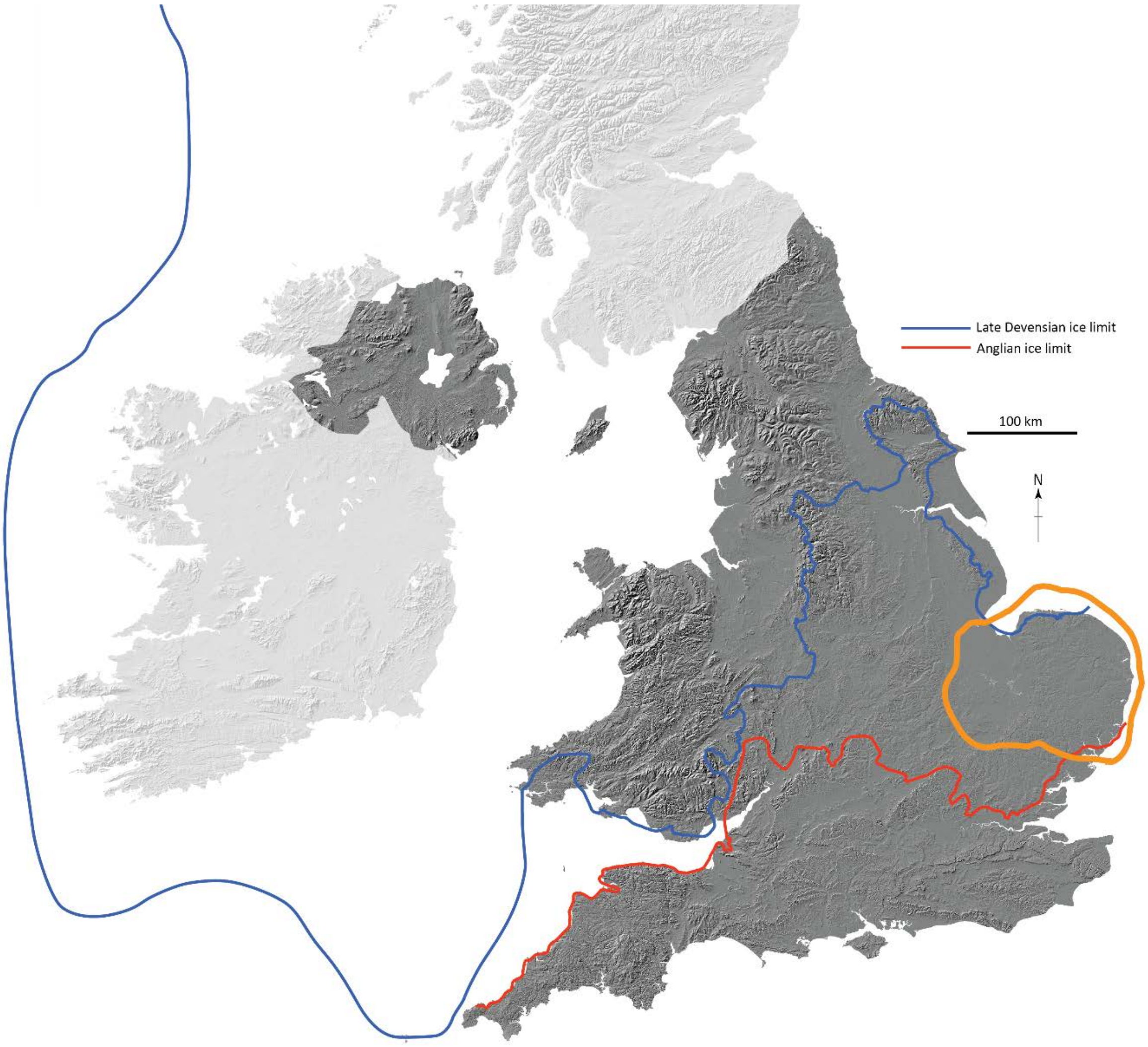


Figure 23 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (approximately 480 to 430 ka) and late Devensian (approximately 30 to16 ka). The location of the East Anglia is delineated by the orange line. Produced using Copernicus 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 23) 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 East Anglia will be subjected to the development of permafrost to a depth of a few hundred metres. The development of permafrost can affect groundwater chemistry and behaviour and, in combination with possible localised glacial erosion in highland areas, future development of permafrost may extend beyond several hundred metres beneath the current ground surface (Busby et al., 2014; RWM 2016b).

7.4 SEISMICITY

7.4.1 A UK-scale context

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

Earthquake activity is greatest at the boundaries between the Earth's tectonic plates, where the differential movement of the plates results in repeated accumulation and release of strain (Figure 24). 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 24). 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).

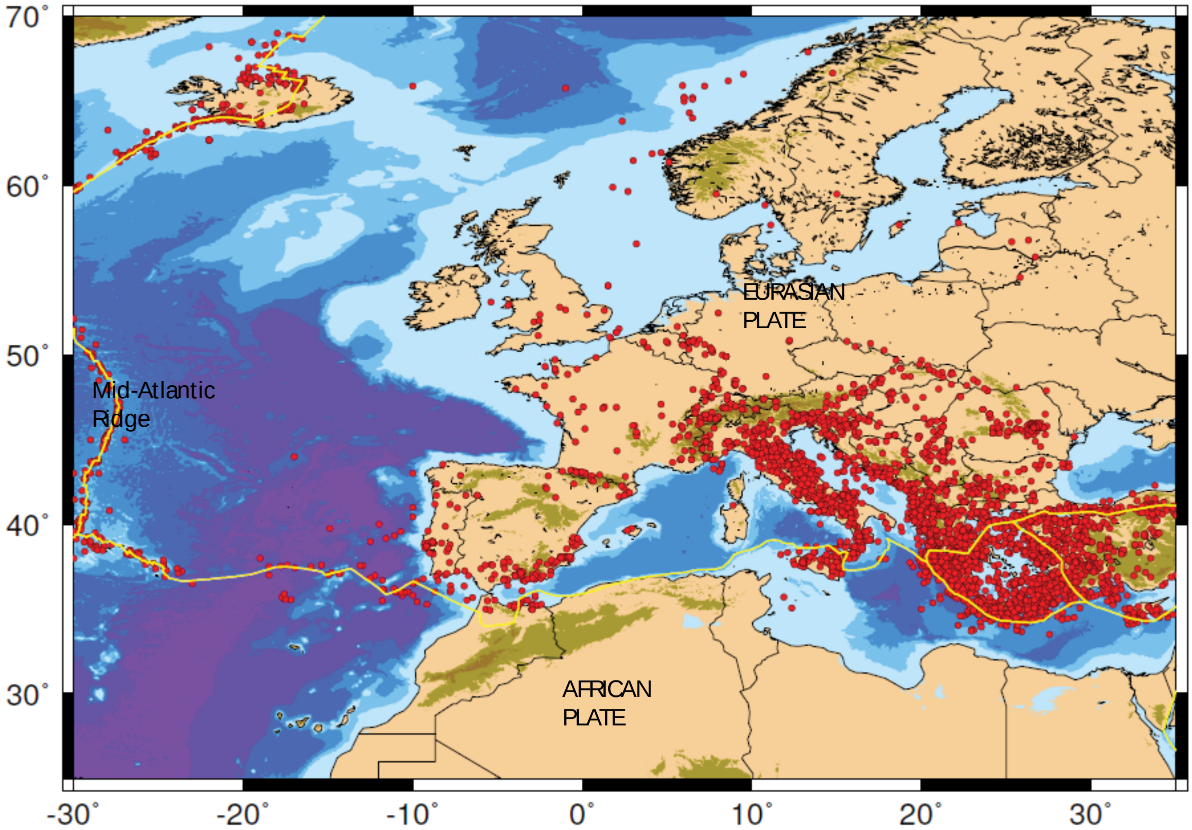


Figure 24 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated 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 4. The catalogue for earthquakes of Mw 3 and above is complete from 1970, i.e. the beginning of the instrumental monitoring of the British earthquakes. The catalogue is complete for earthquakes above Mw 4 and Mw 5 from 1750 and 1650, respectively. In south-east England, the catalogue extends further back in time (to the 14th century) for earthquakes of Mw 5.5 and above.

Table 4 Completeness values for the BGS seismicity catalogue (after Musson and Sargeant, 2007).

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

Figure 25 shows a map of all of the main shocks in the catalogue. The symbols are scaled by magnitude (Mw). It is worth noting that the location uncertainty is ±5 km for instrumental earthquakes and up to ±30 km for historical earthquakes (Musson, 1994). An analysis of the British seismicity clearly shows that it is not correlated with the major tectonic structures that bound the tectonic terranes in the UK (Musson, 2007). The terranes are homogeneous in terms of crustal properties (e.g. distribution and style of faulting), but the seismicity within each block is heterogeneous (Musson, 2007). There are spatial variations in the level of seismic activity across the UK. Western Scotland, western England, Wales, south-western Cornwall and the area off the coast of the south-eastern England are the areas of highest activity. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free (Figure 25).

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 25), which does not correspond to an intense instrumental seismicity. The Dover Straits area is notable for having produced relatively major (≥5 Mw) earthquakes in historical times (the last in 1580) and very little since.

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

7.4.3 Earthquake depths

No earthquake in the UK recorded either historically or instrumentally is known to have produced a surface rupture. Typical fault dimensions for the largest recorded British earthquakes are of the order of 1 to 2 km. Therefore, it is difficult to accurately associate earthquakes with specific faults, particularly at depth, where the fault distributions and orientations are unclear and because of the uncertainties associated with depth estimates. The uncertainties in the focal depths determined for earthquakes are generally large, up to a standard deviation of ±10 km. Figure 26 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 26).

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.

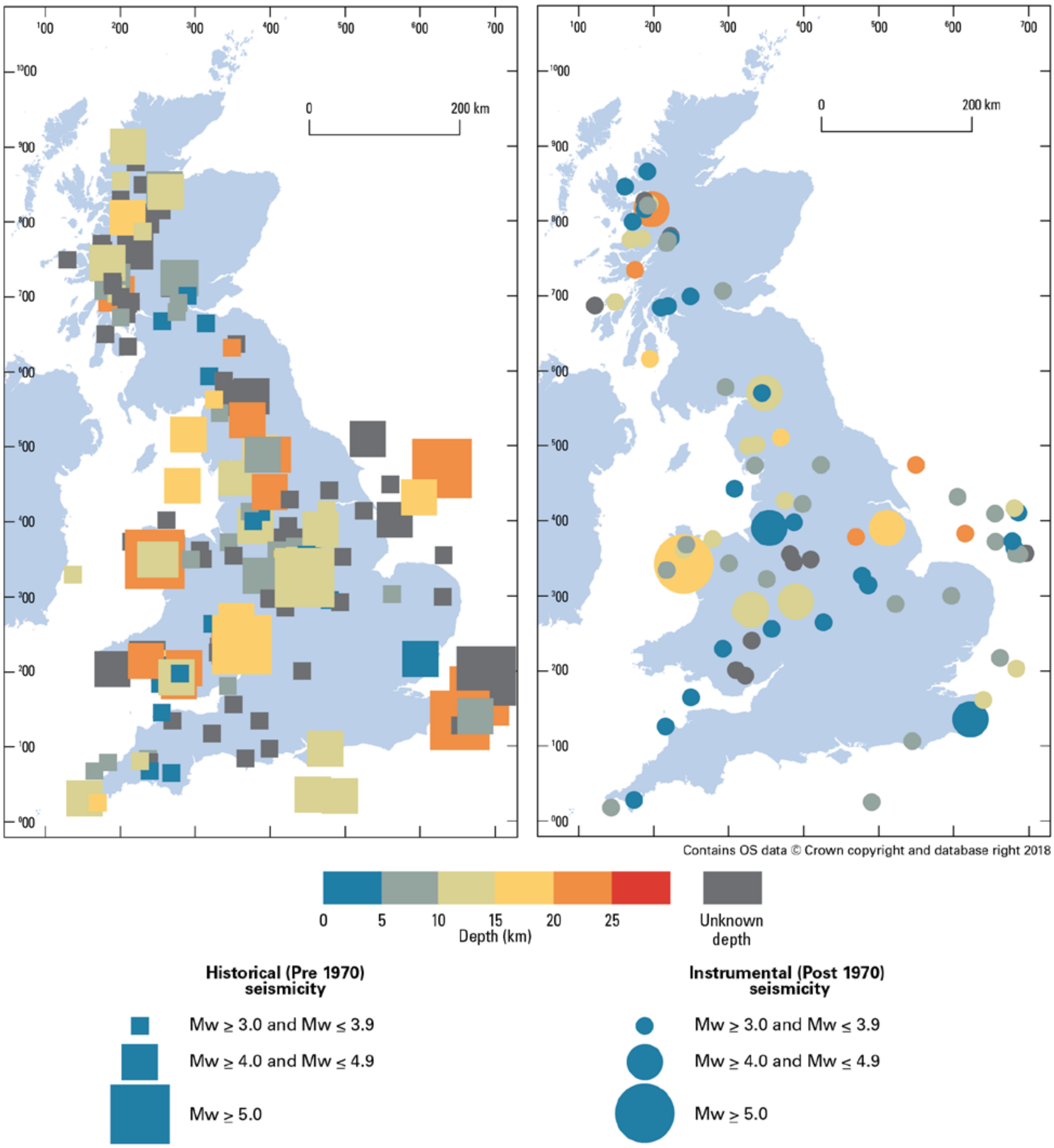


Figure 25 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290' Contains British Geological Survey digital data © UKRI 2018**.**

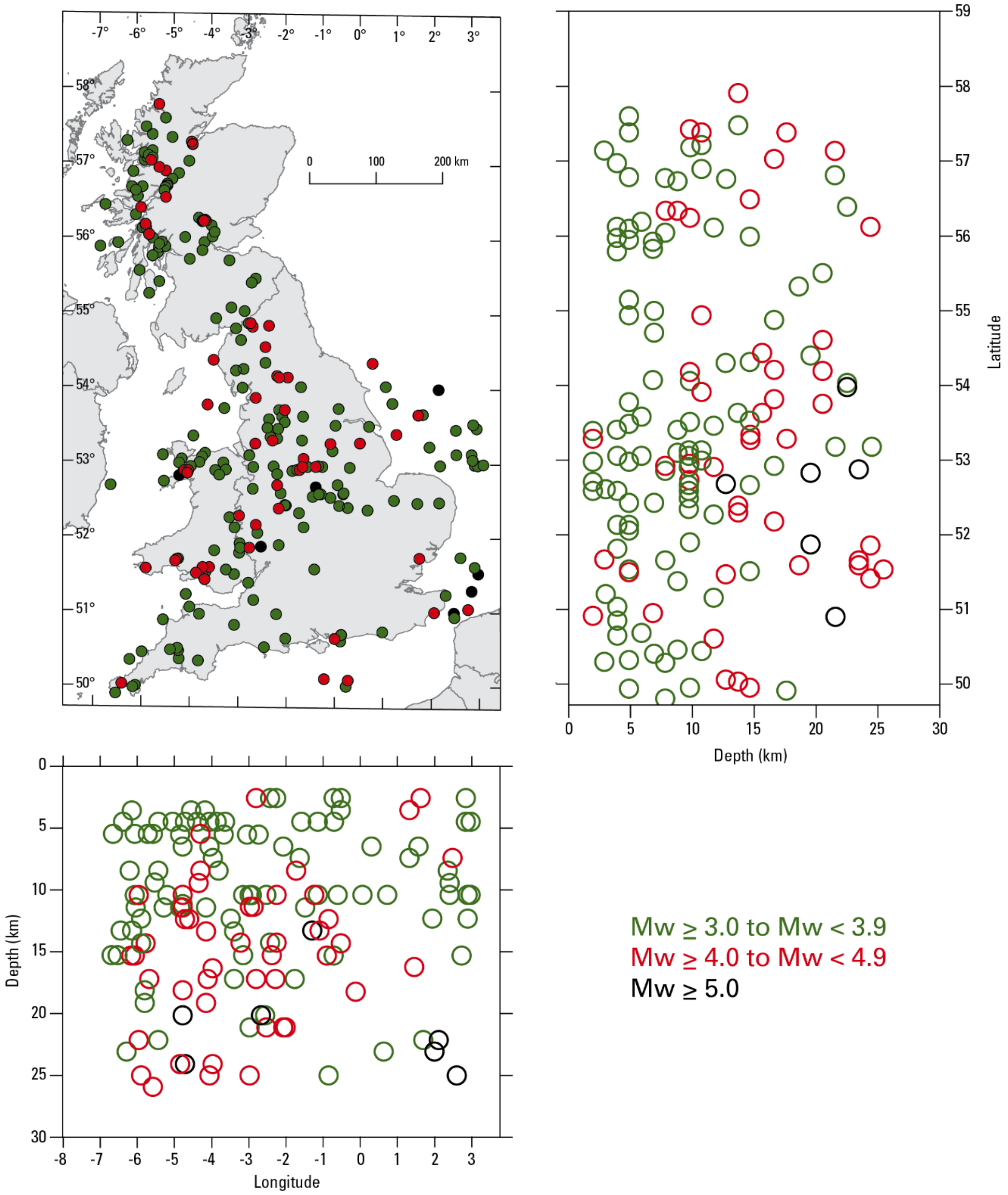


Figure 26 Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290' Contains British Geological Survey digital data © UKRI 2018.

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

Log $N = a - b$ 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

Levels of seismicity in East Anglia are relatively low compared with other parts of Britain (Figure 27). There are no records of earthquakes with magnitudes of Mw 4.0 or greater. A magnitude Mw 3.7 earthquake 30 km west-south-west of Norwich in 1994 was felt in and around Norwich.

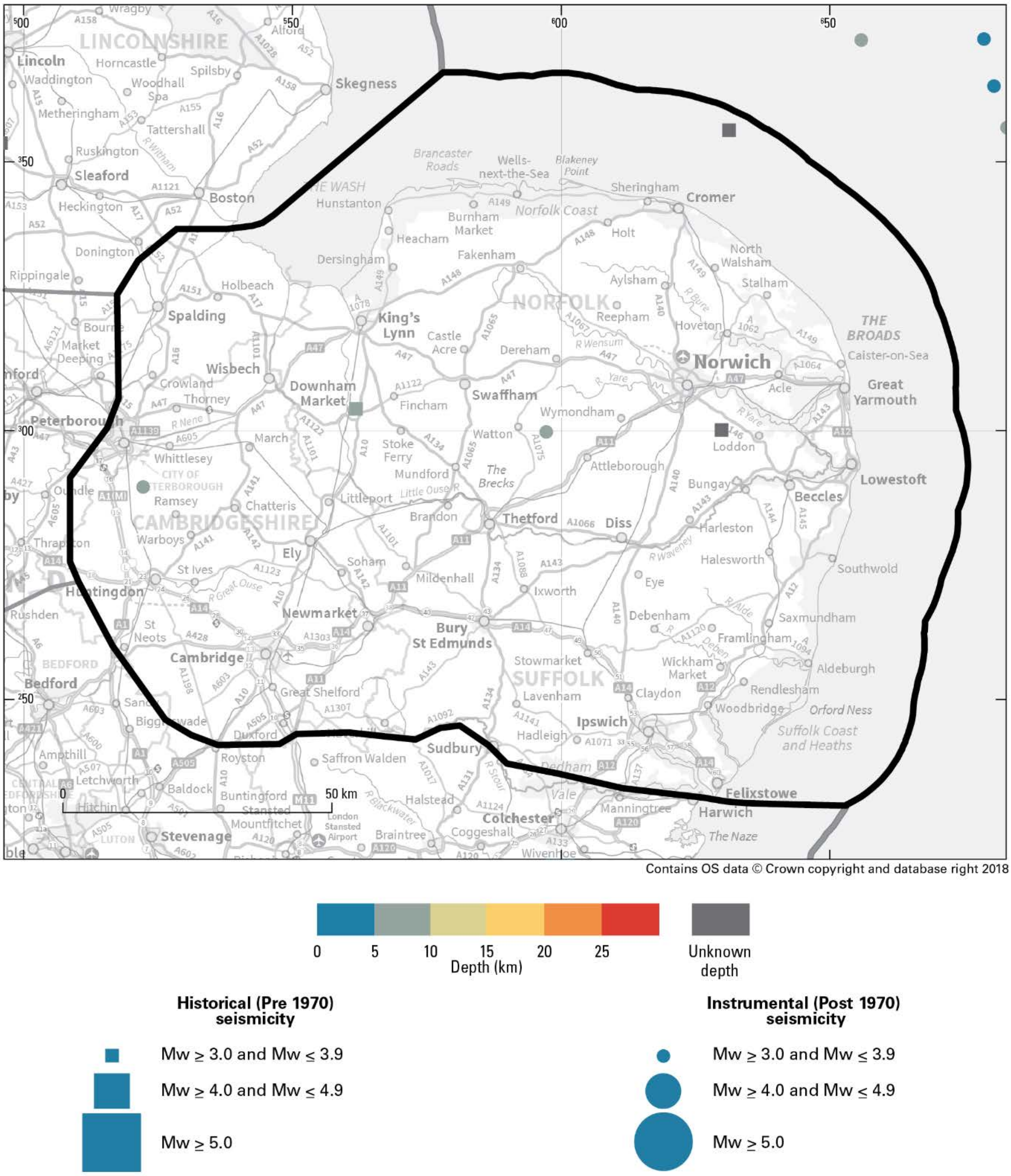


Figure 27 Historical and instrumentally recorded earthquakes in the East Anglia region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290' Contains British Geological Survey digital data © 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 East Anglia region. The extent of possible resources for groups of commodities is described, followed by the presence of any current workings or industrial infrastructure and their associated depths. The resources topic (Table 1) covers a wide range of commodities that are known to be present, or thought to be present, below NGS datum at depths greater than 100 m. These are grouped here into sections consisting of

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

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

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

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

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

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

8.2 OVERVIEW OF RESOURCES IN THE REGION

Figure 28 shows the distribution of mineral resources in the region. The East Anglia region has undergone no past resource exploitation at depths greater than 100 m below NGS datum. With the exception of very deep coal resources in the north-east of the region, there are no known unexploited resources at depths greater than 100 m below NGS datum. There are very few clusters of boreholes greater than 200 m below NGS datum.

8.3 COAL AND RELATED COMMODITIES

There are very deep (greater than 1200 m below NGS datum) coal seams underlying the extreme north-east of the region and the offshore areas to the north and north-east. These have not been exploited or evaluated in detail, however, there is potential for future offshore underground coal gasification.

There are no current licences for coal bed methane, or coal gasification.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

No evaporite mineral resources are known in the region.

8.5 OTHER BEDDED AND MISCELLANEOUS COMMODITIES

There are no deposits of bedded or other miscellaneous deposits that have been worked deeper than 100 m below NGS datum in the region. Chalk, flint and oil shale have all been mined at shallow depths and surface deposits of iron ore have been exploited from quarries in the past.

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 no conventional hydrocarbon fields on or offshore in the region. The most south-westerly of the Southern North Sea gas fields is located within about 25 km of the east coast of the region. There is no potential for shale gas/oil resources in the region.

8.8 GAS STORAGE

There are no planned, under-construction or operating underground gas storage facilities in the region. Whilst there were early assessments at locations in the west of the region, notably around Huntingdon, during the 1960s for town gas storage in porous rocks there seems little immediate prospect for gas storage in the region, including the offshore area being considered.

8.9 GEOTHERMAL ENERGY

There are no deep geothermal heating systems currently operating in the region. There is little geothermal potential in the region because of a lack of large granite intrusions or deep porous sedimentary basins.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are very few clusters of deep (greater than 200 m below NGS datum) boreholes in the region (see Figure 29).

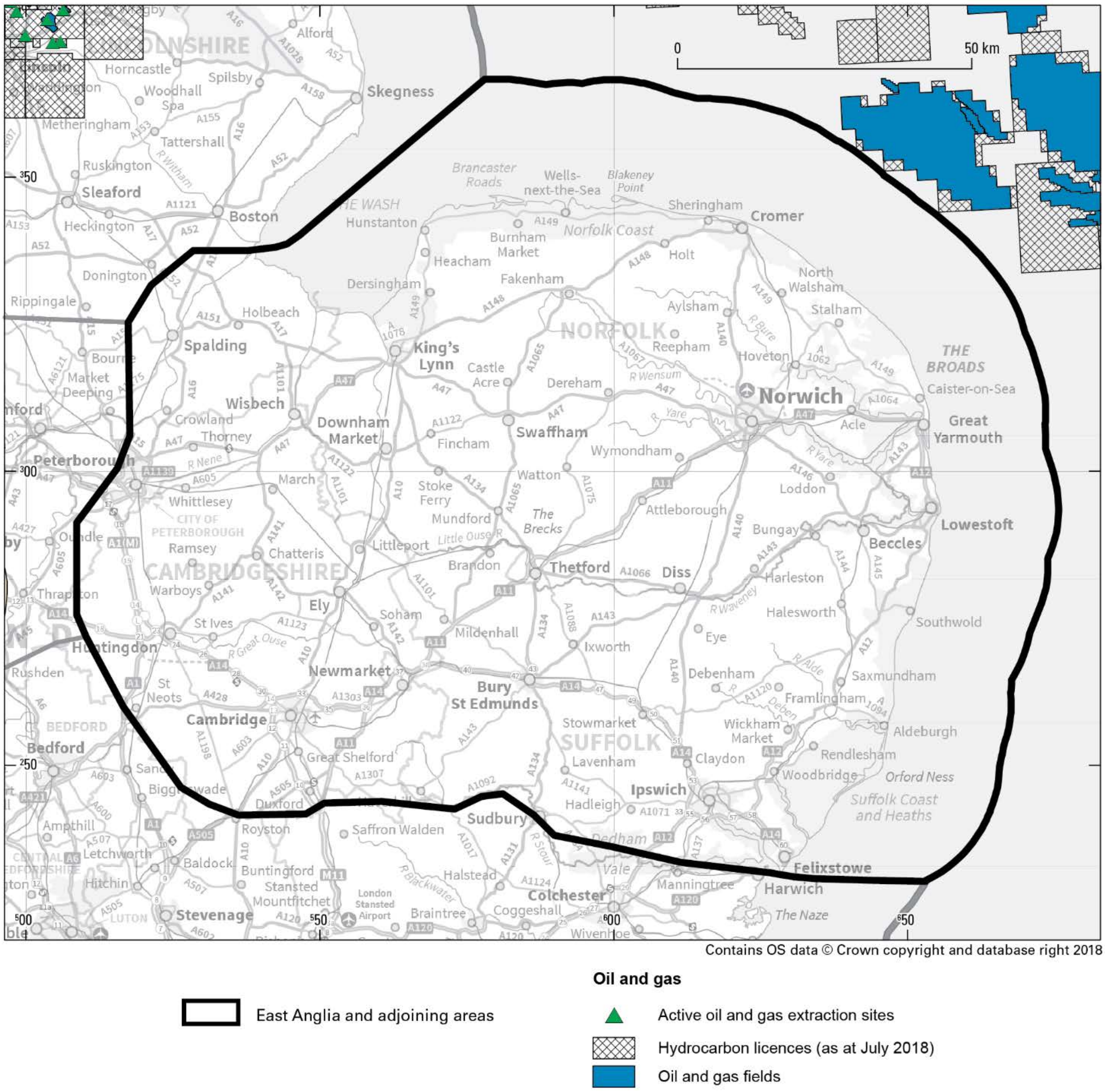


Figure 28 Distribution of mineral resources in the East Anglia region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields 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.

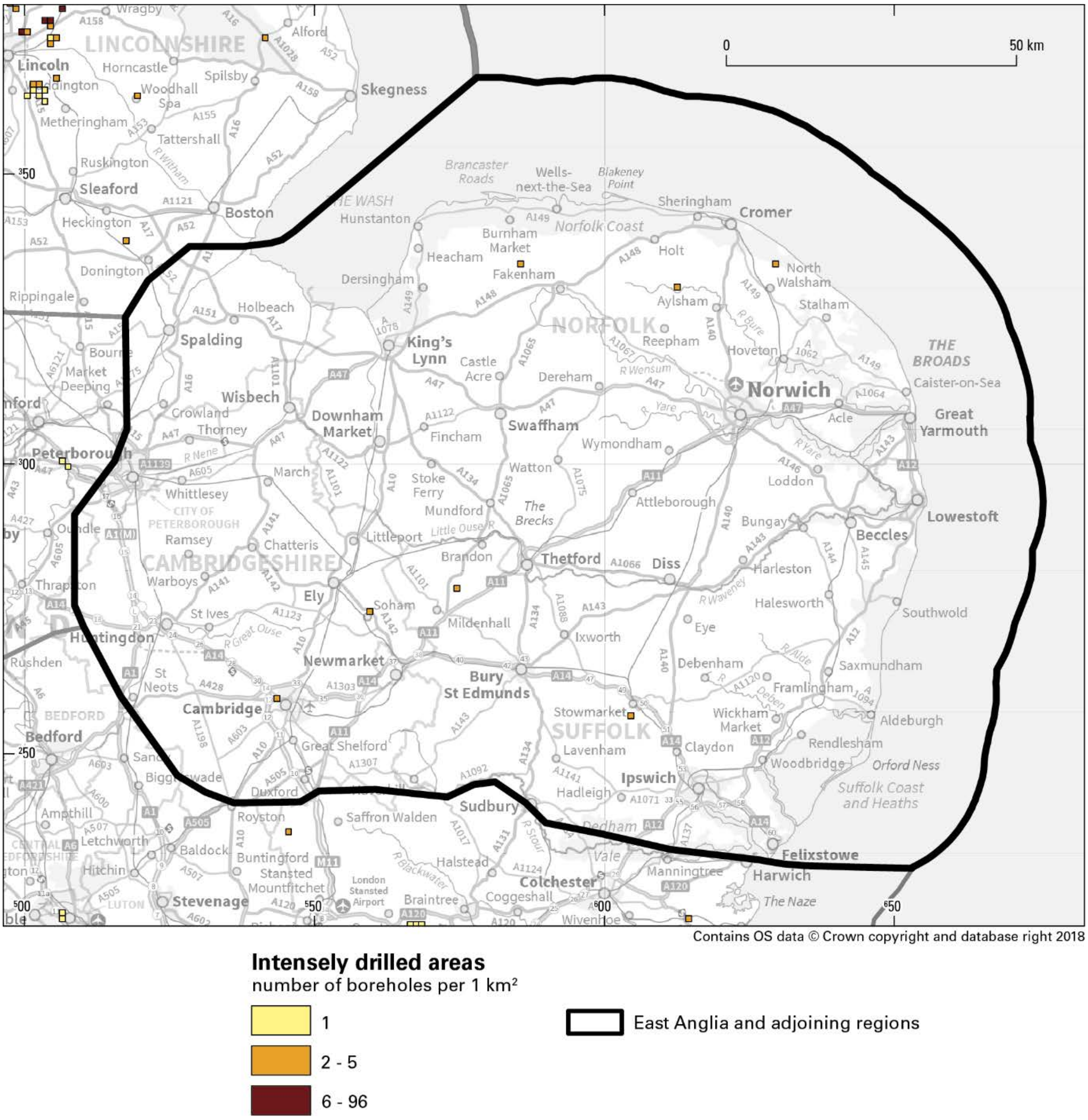


Figure 29 Location of intensely drilled areas in the East Anglia region, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290' Contains British Geological Survey digital data © UKRI 2018.

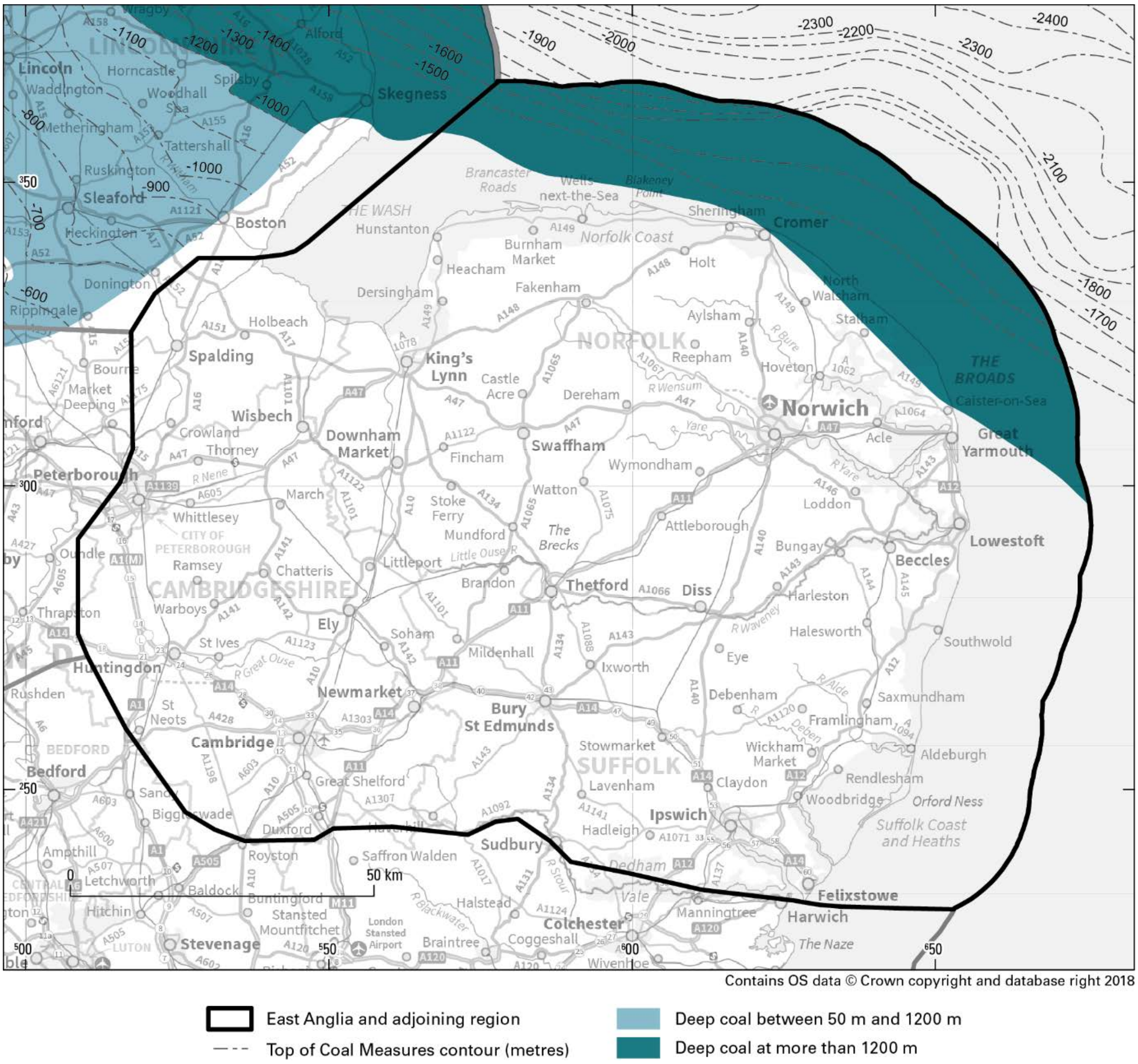


Figure 30 Distribution of coal resources in the East Anglia region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290' Contains British Geological Survey digital data © UKRI 2018

8.11 SUPPORTING INFORMATION

8.11.1 Borehole depths

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

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

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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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Resources

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.

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).