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National Geological Screening: London and the Thames Valley

Minerals and Waste Programme

Commissioned Report CR/17/101

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/101

National Geological Screening: London and the Thames Valley

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

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Acronyms and abbreviations

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

Glossary

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

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

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

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

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

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

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

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

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

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

Higher strength rock (HSR) — higher strength rocks, which may be igneous, metamorphic or older sedimentary rocks, have a low matrix porosity and low permeability, with the majority of any groundwater movement confined to fractures within the rock mass (RWM, 2016a).

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

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

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

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

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

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

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

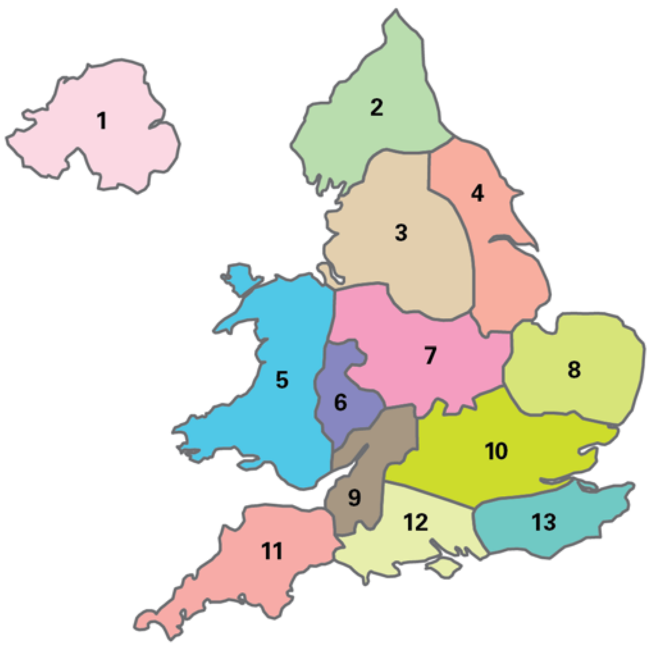
Principal aquifer — a regionally important aquifer defined by the Environment Agency as layers of rock that have high intergranular and/or fracture permeability, meaning they usually provide a high level of water storage (Environment Agency, 2013).

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

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

1 Introduction

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

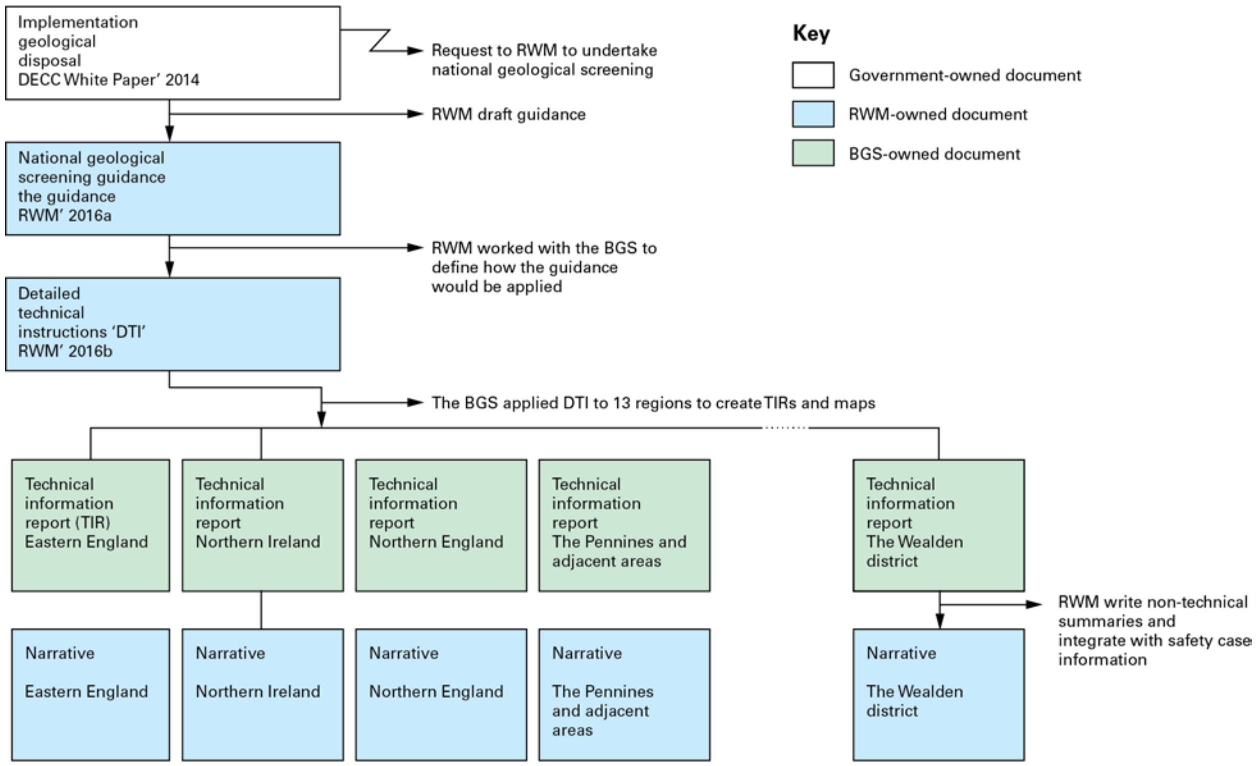


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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 Thames Valley region

This region covers the great majority of the River Thames catchment. The northern margin follows the county boundaries of Wiltshire, Oxfordshire, Buckinghamshire, Bedfordshire, Hertfordshire and Essex to meet the North Sea coast at Harwich. The southern margin is an arbitrary line across Wiltshire and then it largely follows geological boundaries through Berkshire, eastwards along the North Downs to the Thames estuary near Rochester.

The landscape, shaped by the underlying geology, includes part of the Cotswold Hills, the broad clay vales in which Oxford and Bedford are situated, the chalk hills of the Marlborough Downs, Berkshire Downs, Chiltern Hills and North Downs, and gently undulating clay-dominated areas of Essex and Greater London.

The relatively shallow geology is well documented, based on geological mapping, evidence from surface exposures and boreholes drilled for site investigation and water. The deeper geology is less well known but proved in about 50 boreholes, some more than 1000 m deep, drilled for oil, coal and gas exploration, water abstraction or scientific research. Further evidence of the deeper geology is provided by the interpretation of a limited number of seismic reflection lines, mainly in the south-west and far west of the region (Whittaker, 1985) and UK regional gravity and magnetic data. A collation of information on the subsurface is provided by the NGS3D model constructed from a series of cross-sections that utilise many of the deep borehole data and an interpretation of the regional gravity and magnetic data.

3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

The geology at surface in the region is shown in Figure 5. Figure 6 and 7 illustrate the geological variation across the region. The reader is referred to the regional summary on the BGS website (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html) for a non-technical overview of the geology of the region and to national geological screening: Appendix A (Pharaoh and Haslam, 2018) for an account of the formation and structure of the basement, and the older and younger sedimentary cover rocks of the UK.

Deep boreholes in the region prove that the Mesozoic and younger rocks rest on a basement of Neoproterozoic to Palaeozoic age. These basement rocks are similar to those that crop out in Wales, parts of the Midlands and northern England. Generally they lie at more than 1.5 km below NGS datum in parts of the west and south of the region whereas in central and eastern parts they are at much shallower depth, forming the London platform. It is some 300 m deep beneath central London and around 100 m in parts of Oxfordshire, Buckinghamshire and Bedfordshire (Figure 3).

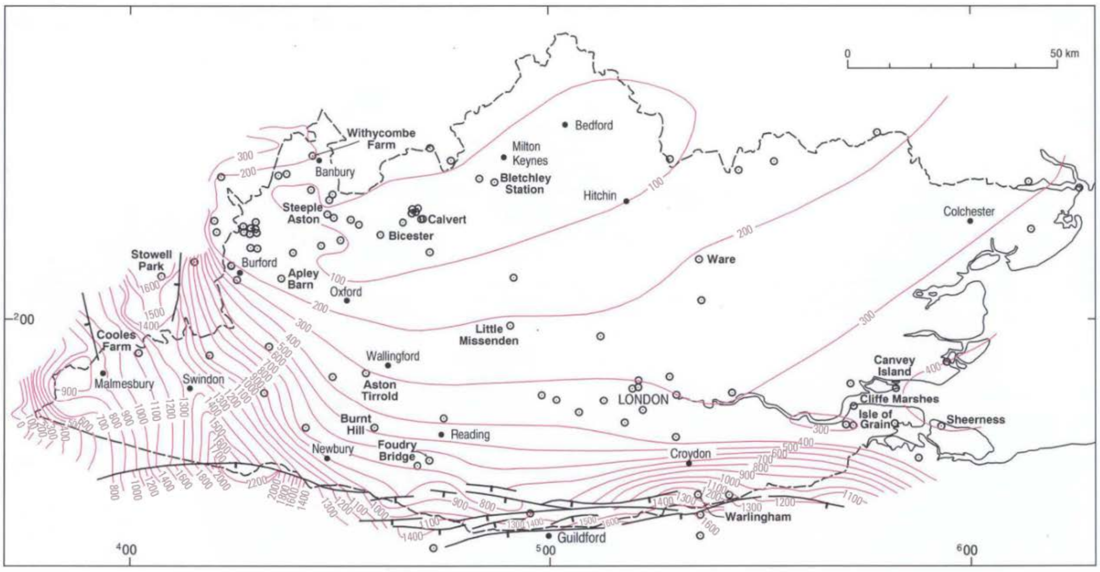


Figure 3 Contours on the surface of the Precambrian and Palaeozoic basement. Contours are in metres below Ordnance Datum (from Sumbler, 1996). British Geological Survey © UKRI 2018.

The London platform remained as a relatively stable structural high throughout the Mesozoic and Cenozoic and therefore exerted a significant influence on sedimentation during that time. North of the platform, Mesozoic sediments gradually thicken into an area known as the East Midlands shelf. By contrast, in the far west and south of the region fault-bounded sedimentary basins, the Worcester and Wessex basin respectively, provided deep sediment traps in Mesozoic times (Figure 4).

The Mesozoic history of the region is essentially one of gradual but discontinuous sedimentary infill of the basins and encroachment of sediments onto the London platform although the latter probably did not become entirely buried until Cretaceous times.

The pattern of outcrop of the Mesozoic and Cenozoic rocks of the region is related to the geological structure that is dominated by the broad, gentle synclinal fold, open to the east, which underlies London. Its axis is traced from Marlborough in the west through Newbury, Chertsey and north London to beyond the coast of Essex. The oldest Mesozoic rocks at the surface are found at the edge of the syncline with progressively younger ones towards the centre as illustrated in Figures 5, 7 and 12.

On the north-west limb of this main fold the rocks dip gently to the south-east, generally at less than 1º. As a consequence the rock unit outcrops trend approximately south-west to north-east. Harder beds form ranges of hills and softer beds the intervening vales. These units on the north-west flank of this large-scale syncline include all the PRTIs in the region. On the south limb of the main fold the rocks generally dip at up to 3º but locally steepen to 50–60º along the Hog’s Back ridge near Guildford along a major fault system on the northern edge of the Wessex basin.

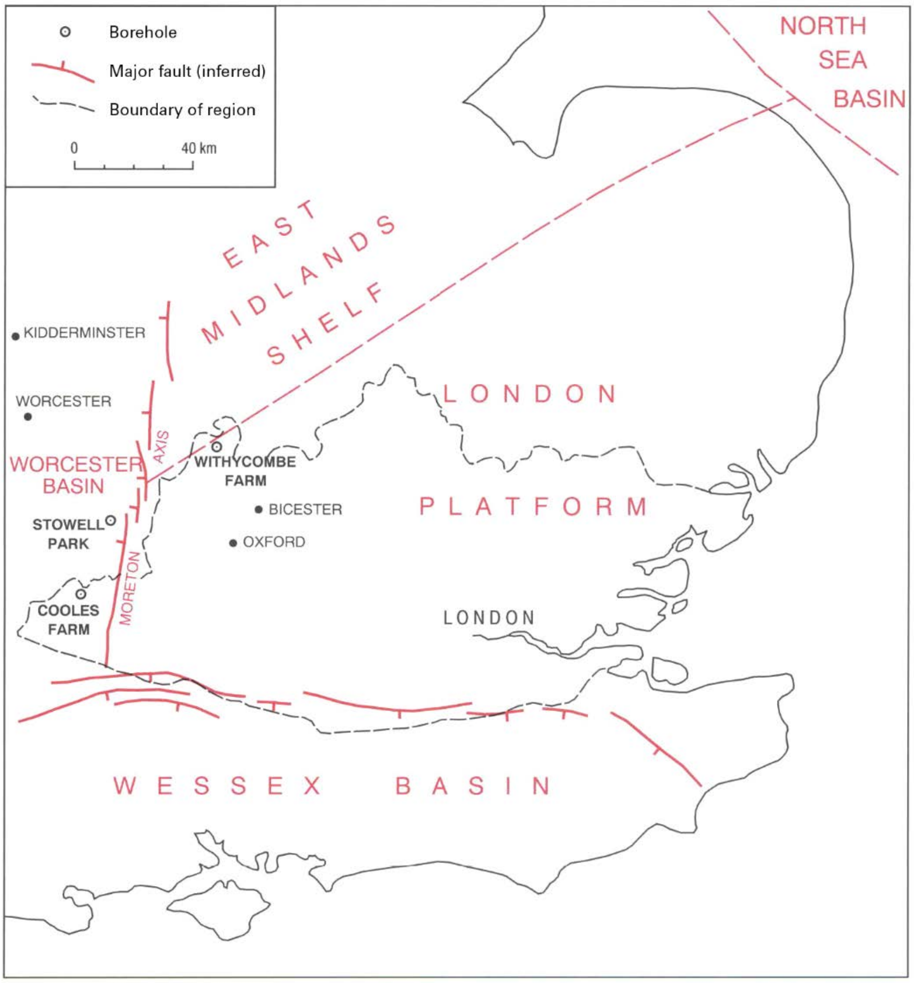
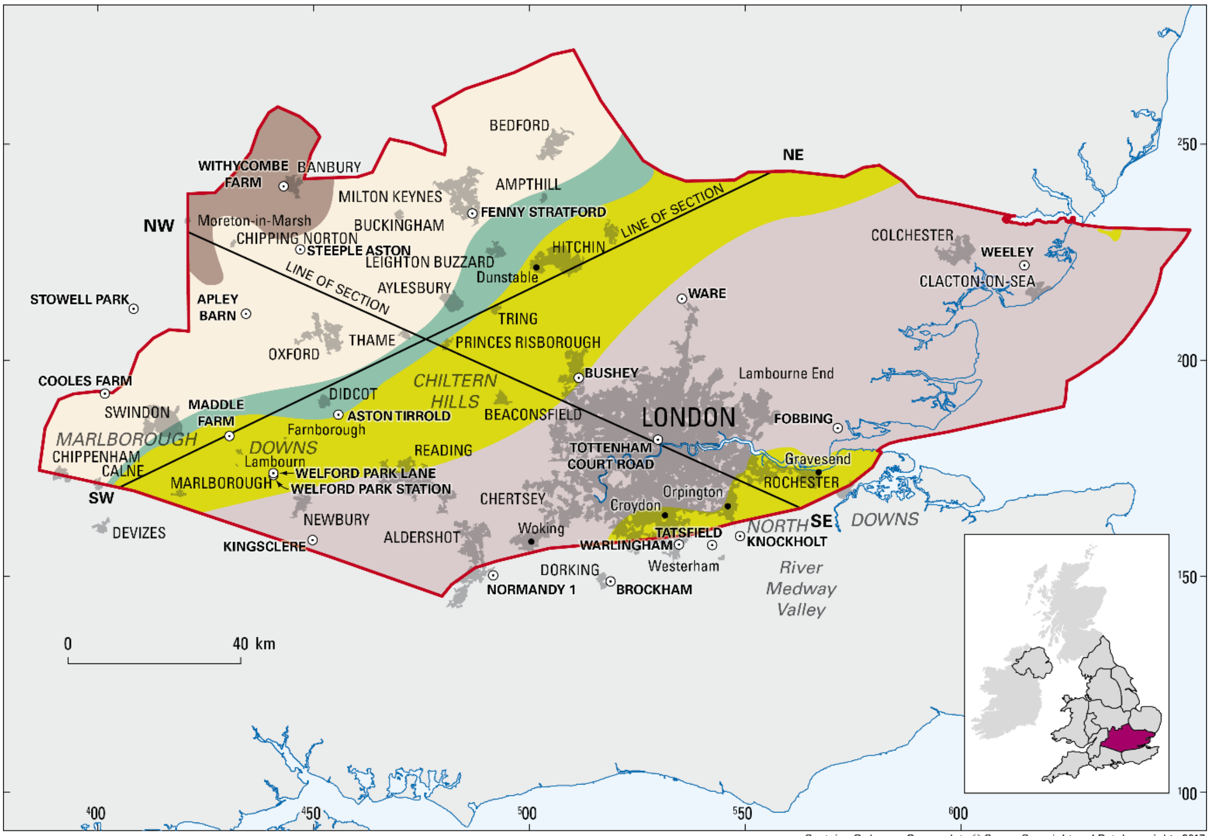


Figure 4 Principal structural elements in the Thames Valley region. The faults, shown as solid red lines with a tick on the downthrow side, were active during sedimentation of the Mesozoic rocks (from Sumbler, 1996). British Geological Survey © UKRI 2018.



Age (Ma)	Map/section descriptor	Geological sub-units	Text descriptor
50–65	Palaeogene sediments	Barton Group Bracklesham Group Thames Group Lambeth Group and Thanet Formation	Younger sedimentary rocks
80–145	Late Cretaceous sedimentary rocks	Chalk Group	
		Upper Greensand and Gault formations and Lower Greensand Group	
	Early Cretaceous sedimentary rocks	Wealden Group	
145–200	Mid and Late Jurassic sedimentary rocks	Purbeck and Portland groups Ancholme Group Oolite groups (Great and Inferior)	
	Early Jurassic sedimentary rocks	Lias Group	
200–250	Triassic and Permian sedimentary rocks	Mercia Mudstone Group Sherwood Sandstone Group Permian rocks	
310–350	Carboniferous sedimentary rocks	Warwickshire Group Pennine Coal Measure Group Carboniferous Limestone Supergroup	Older sedimentary rocks
360–420	Devonian sedimentary rocks		Basement rocks
420–500	Early Palaeozoic–Neoproterozoic	Mudstones, siltstones and sandstones with minor volcanics	

Figure 5 Generalised geological map and key showing the distribution of younger sedimentary rocks, older sedimentary rocks and basement rocks in the onshore Thames Valley region. The inset map shows the extent of the region in the UK. See Figures 6 and 7 for schematic cross-sections. The ‘Geological sub units’ column is highly generalised and does not represent all geological units in the region. Stratigraphical nomenclature and lithological descriptions are simplified and therefore may differ from those used in other sections of this report. The locations of key boreholes mentioned in the text are shown by a circle and dot. Contains public sector information licenced under the Open Government Licence v3.0. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

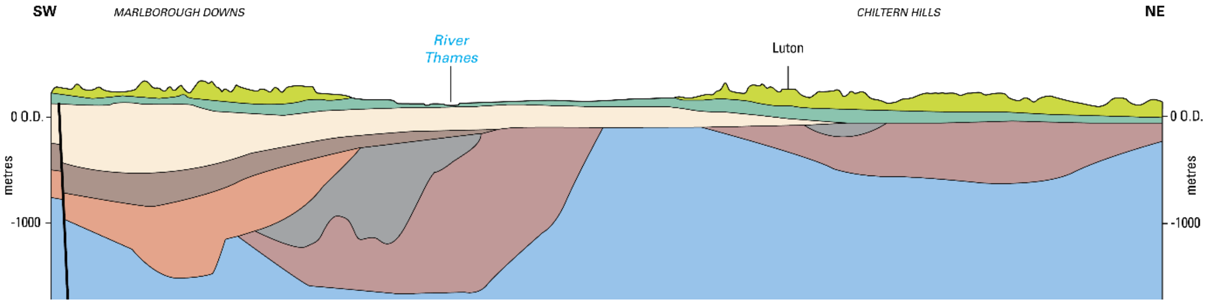


Figure 6 Schematic south-west to north-east cross-section through the Thames Valley region. Line of section and key are shown in Figure 5. British Geological Survey © UKRI 2018

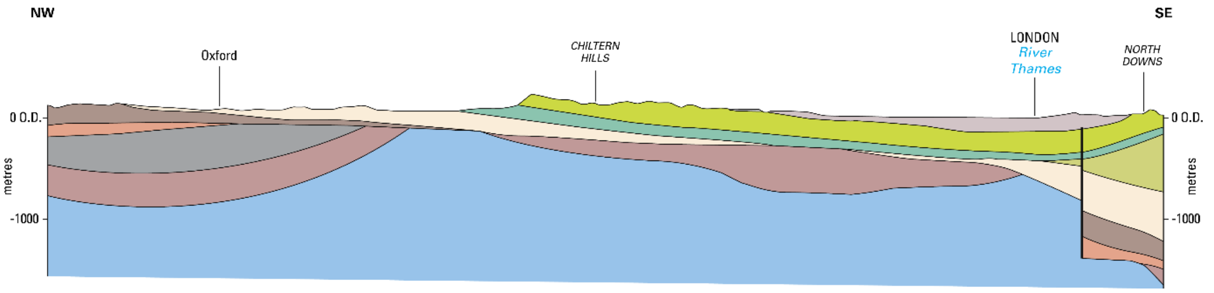


Figure 7 Schematic north-west to south-east cross-section through the Thames Valley region, passing through London. Line of section and key are shown in Figure 5. British Geological Survey © UKRI 2018

3.1.1 Geological data and confidence

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

In the Thames Valley region, the spatial extent and composition of the sedimentary cover rocks is fairly well known and documented from surface geological mapping, evidence from surface exposures and/or shallow boreholes. Younger, near-surface units in the cover are fairly well known from surface geological mapping while Triassic and older units are concealed and proved by deeper boreholes and/or inferred by seismic data (such as the Permian mudstones).

In the depth range of interest, information on PRTI units within the cover rocks is constrained by deeper boreholes and seismic profile data. For example, the central west part of the area underlain by the Warwickshire Group is well constrained from coal exploration boreholes.

Many aspects of the extent and composition of the deeper rocks, in particular the basement units of the Thames Valley region, are known only in outline: there is too little information to be confident about many of the details. Although the basement rocks (crystalline basement and early Palaeozoic sedimentary rocks) are proved in about 50 boreholes (Figure 17 shows all boreholes intersecting basement rocks), only the uppermost few meters are penetrated with few lithological details. Furthermore, these boreholes are primarily centred on the Oxfordshire and Berkshire coalfield area in the central west of the region. Only a very limited number of boreholes penetrate the basement in areas around London and beyond. Further evidence of the deeper geology is provided by the interpretation of a very limited number of seismic reflection lines and regional gravity and aeromagnetic geophysical data. In the east of the region, knowledge of the geology is revealed only by the regional gravity and aeromagnetic fields, corroborated by the relatively few boreholes that penetrate the base of the Mesozoic strata in the region. In contrast, seismic surveys have been carried out in much of the west of the region, and together with deep boreholes and the regional potential field maps, these have provided detailed constraints on the geological and structural interpretation of that area.

As discussed in previous sections, what is known of the composition of the basement within the region largely depends on what can be inferred from a small number of boreholes, interpretation of geophysical information, and knowledge of contiguous, or analogous, terranes outside the region. Analogues for the Variscan fold belt can be found in parts of Devon and Cornwall, but these areas are more than 150 km away. The Caledonian fold belt can be assumed to resemble counterparts in Wales, Cumbria and southern Scotland. The Neoproterozoic basement of the Charnwood terrane is exposed only in rather small areas of Leicestershire and Warwickshire. Each of the basement terranes can be expected to include some folded and metamorphosed elements but direct observation of their component rock units is limited to a small number of deep boreholes, and thus is highly uncertain. The relatively sparse borehole information means that the degree of heterogeneity in the composition of the basement terranes is also poorly known.

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 THAMES VALLEY REGION

Table 3 presents a generalised vertical section (GVS) for the Thames Valley region identifying the PRTIs that occur between 200 to 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 Thames Valley region, the GVS groups the rocks into three age ranges: younger sedimentary rocks (Triassic to Palaeogene), older sedimentary rocks (Carboniferous) and basement rocks (Devonian and early Palaeozoic rocks and older) (Table 3, Column 1). Some of the rock units in the region are considered to represent PRTIs present within the depth range of interest, between 200 to 1000 m below NGS datum. These include a number of lower strength sedimentary rock units (LSSR) with one higher strength rock (HSR) unit occurring on the northern margins of the region. There are no evaporite PRTIs in the region. The Barton Group, Bracklesham Group, Thames Group, Lambeth Group and Permian rocks, shown on Figure 5, do not occur in the depth range of interest in this region and therefore are not considered suitable PRTIs and are not discussed further. The majority of the basement rocks in the region, comprising early Palaeozoic sediments of Cambrian, Ordovician, Silurian and Devonian age (Figure 17), lie outside established cleavage belts (Acadian and Variscan) and it is not known whether the mudstone component of these rocks preserves a pervasive cleavage and are sufficiently compacted and metamorphosed. Because of this they are not considered to be a PRTI and are not considered further. Charnian Supergroup rocks in the extreme north-west of the region are below the depth range of interest and are not discussed further

The PRTIs are described in Table 3 in stratigraphical order from youngest to oldest (i.e. in downward succession), grouped by the three age ranges: younger sedimentary rocks, older sedimentary rocks and basement rocks. The descriptions include the distribution of the PRTI at surface (outcrop) and where the PRTI is present below the surface (subcrop) within the depth range of interest, along with key evidence for the interpretations. The main geological properties of the PRTIs and how these vary across the region are also summarised. Data are from a range of publications such as the BGS Regional Guide to the London and the Thames Valley region (Sumbler, 1996) 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 locations of boreholes referred to in this chapter are shown on Figure 5.
The UK3D model (see glossary) was used as an information source for estimating the presence, thickness, depth of occurrence of the geological units discussed, and the geometry of their boundaries. Interpretations based on this model rely on borehole-derived geological relationships depicted in cross-sections, and it is possible that understanding of these relationships in some areas may be limited by cross-section data availability.

Maps showing the regional distribution of PRTIs between 200 and 1000 m below NGS datum for the three generic host rock types are provided in Figures 8, 9 and 10. A summary map showing the combined distribution of all PRTIs is provided in Figure 11.

Table 3 Schematic GVS for the Thames Valley 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 8, 9 and 10 for the distribution of PRTIs amalgamated by host rock model (i.e. LSSR, EVAP and HSR respectively).

Geological period		Geological unit identified in NGS3D	Dominant rock type	Potential rock types of interest			Principal aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS	Palaeogene	Bracklesham and Barton groups	Sand, sandy clay, clay, with flint and chert pebble beds at some horizons, and ironstones locally	N/A	N/A	N/A	N/A
		Thames Group	Sand, silt, clay, locally with volcanic ash horizons	N/A	N/A	N/A	N/A
		Lambeth Group	Sands, sandy clay, clay, sometimes with basal flint conglomerate, local lignite	N/A	N/A	N/A	N/A
		Thanet Formation (Montrose Group)	Silty sand, clayey sand with flint conglomerate at base	N/A	N/A	N/A	N/A
	Cretaceous	Chalk Group	Fine-grained limestone, with thin units of calcareous mudstone and flint	N/A	N/A	N/A	Chalk Group
		Upper Greensand Formation (Selborne Group)	Mudstone and silty mudstone with phosphatic pebbles (Gault); sandstone, locally with chert (Upper Greensand)	N/A	Gault Formation	N/A	Upper Greensand Formation
		Gault Formation (Selborne Group)					N/A
		Lower Greensand Group	Sandstone, pebbly sandstone, mudstone, chert, ironstone	N/A	N/A	N/A	Lower Greensand Group
		Wealden Group	Siltstone, sandstone, mudstone	N/A	Weald Clay Formation	N/A	N/A
	Jurassic to Cretaceous	Purbeck Group	Interbedded limestone, mudstone and sandy mudstone	N\A	N/A	N\A	N/A
	Jurassic	Portland Group	Calcareous sandstone, siltstone, and limestone	N/A	N/A	N/A	N/A
		Ampthill Clay and Kimmeridge Clay formations (undivided); West Walton, Ampthill Clay and Kimmeridge Clay formations (Ancholme Group)	Mudstone, silty mudstone, siltstone, with thin concretionary limestones	N/A	Kimmeridge Clay, Ampthill Clay and West Walton formations	N/A	N/A
		Corallian Group	Limestone, calcareous mudstone, sandstone	N/A	N/A	N/A	N/A
		Kellaways and Oxford Clay formations (Ancholme Group)	Mudstone, silty mudstone, siltstone, with thin concretionary limestones	N/A	Oxford Clay Formation, Kellaways Clay Member	N/A	N/A
		Great Oolite Group	Mudstone, muddy limestone, limestone, sandy limestone, sandstone	N/A	N/A	N/A	Great Oolite Group
		Inferior Oolite Group	Limestone, sandy limestone, ferruginous limestone, siltstone, mudstone	N/A	N/A	N/A	Inferior Oolite Group
		Lias Group	Mudstone, sandstone, limestone including ferruginous limestone, thin conglomerate	N/A	Lias Group	N/A	N/A
	Triassic	Mercia Mudstone Group (including Penarth Group)	Mudstone, siltstone and sandstone with thin layers of anhydrite and gypsum	N/A	Mercia Mudstone Group and Penarth Group	N/A	N/A
		Sherwood Sandstone Group	Red sandstone, siltstone and mudstone	N/A	N/A	N/A	Sherwood Sandstone Group
OLDER SEDIMENTARY ROCKS	Carboniferous	Warwickshire Group	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	N/A	Grovesend Formation	N/A	N/A
		South Wales Coal Measures Group	Mudstone, siltstone, sandstone, coal, with volcanic and intrusive igneous rocks locally	N/A	N/A	N/A	N/A
		Tournaisian–Visean rocks = Carboniferous Limestone Supergroup	Limestone with interbedded mudstone and silty mudstone	N/A	N/A	N/A	Carboniferous Limestone Supergroup

BASEMENT ROCKS	Devonian	Devonian rocks (undivided)	Mudstone, siltstone and sandstone with some limestone locally	N/A	N/A	N/A	N/A
	Early Palaeozoic	Silurian rocks (undivided)	Mudstone, siltstone, sandstone and limestone. Some volcanic rocks locally	N/A	N/A	N/A	N/A
		Cambrian and Ordovician rocks (undivided)	Mudstone, siltstone and sandstone with thin limestone	N/A	N/A	N/A	N/A
	Proterozoic	Avalonian Proterozoic crystalline basement	Granite and basaltic andesite	Granitic intrusion	N/A	N/A	N/A
		Charnian Supergroup	Volcanoclastic rocks (both pyroclastic and reworked volcanic rocks)	N/A	N/A	N/A	N/A

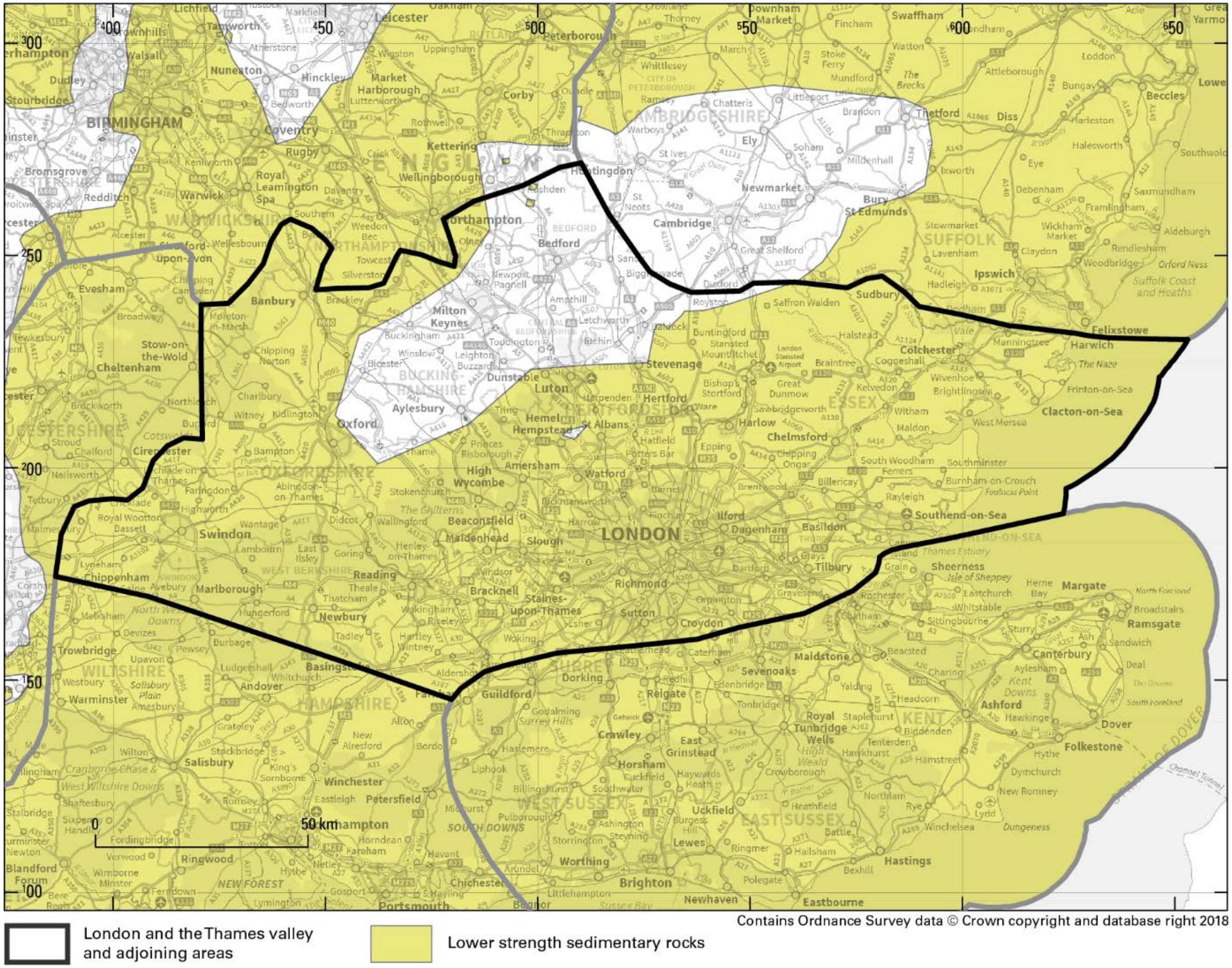


Figure 8 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Thames Valley region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains BGS digital data © British Geological Survey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

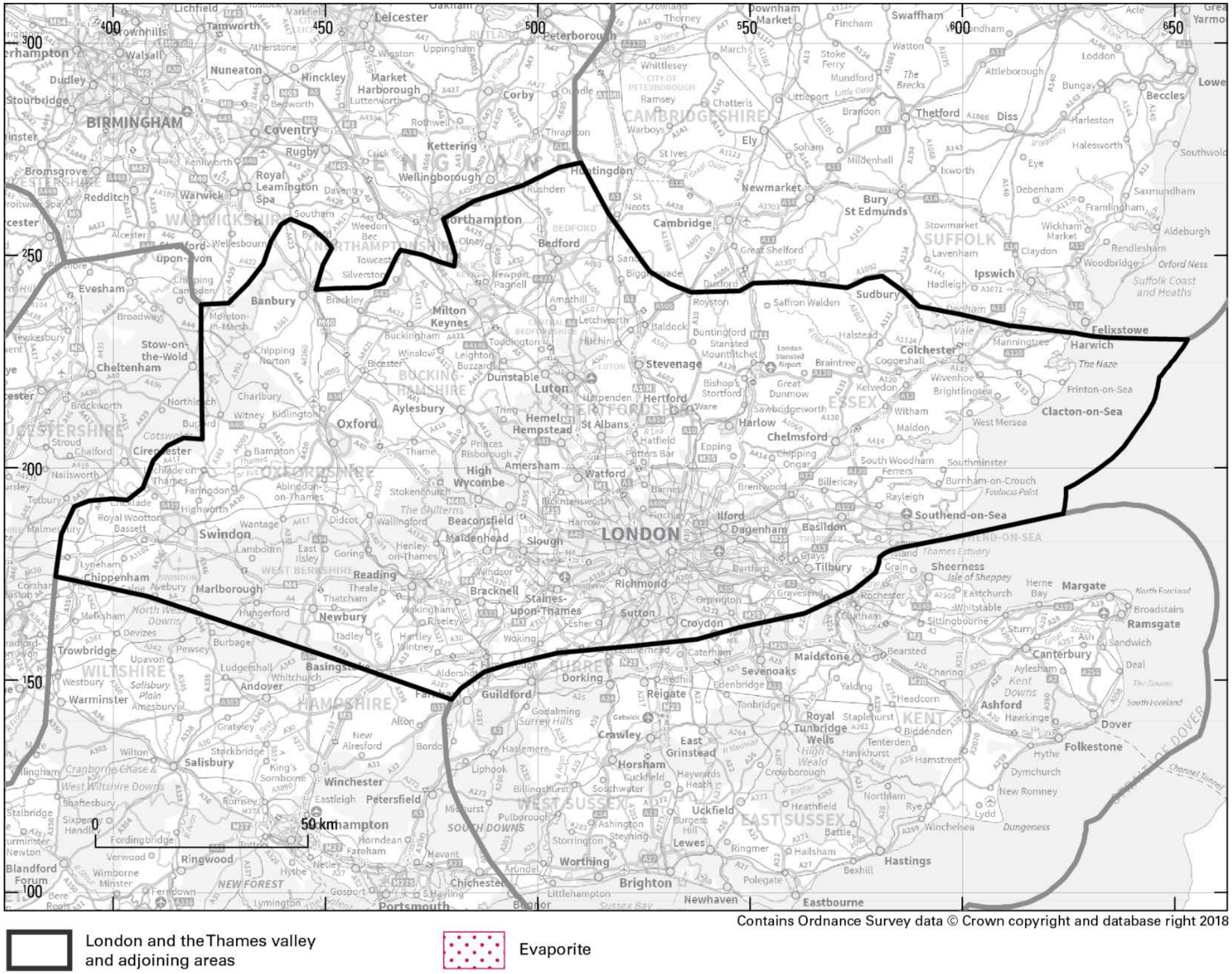


Figure 9 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the Thames Valley region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains BGS digital data © British Geological Survey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

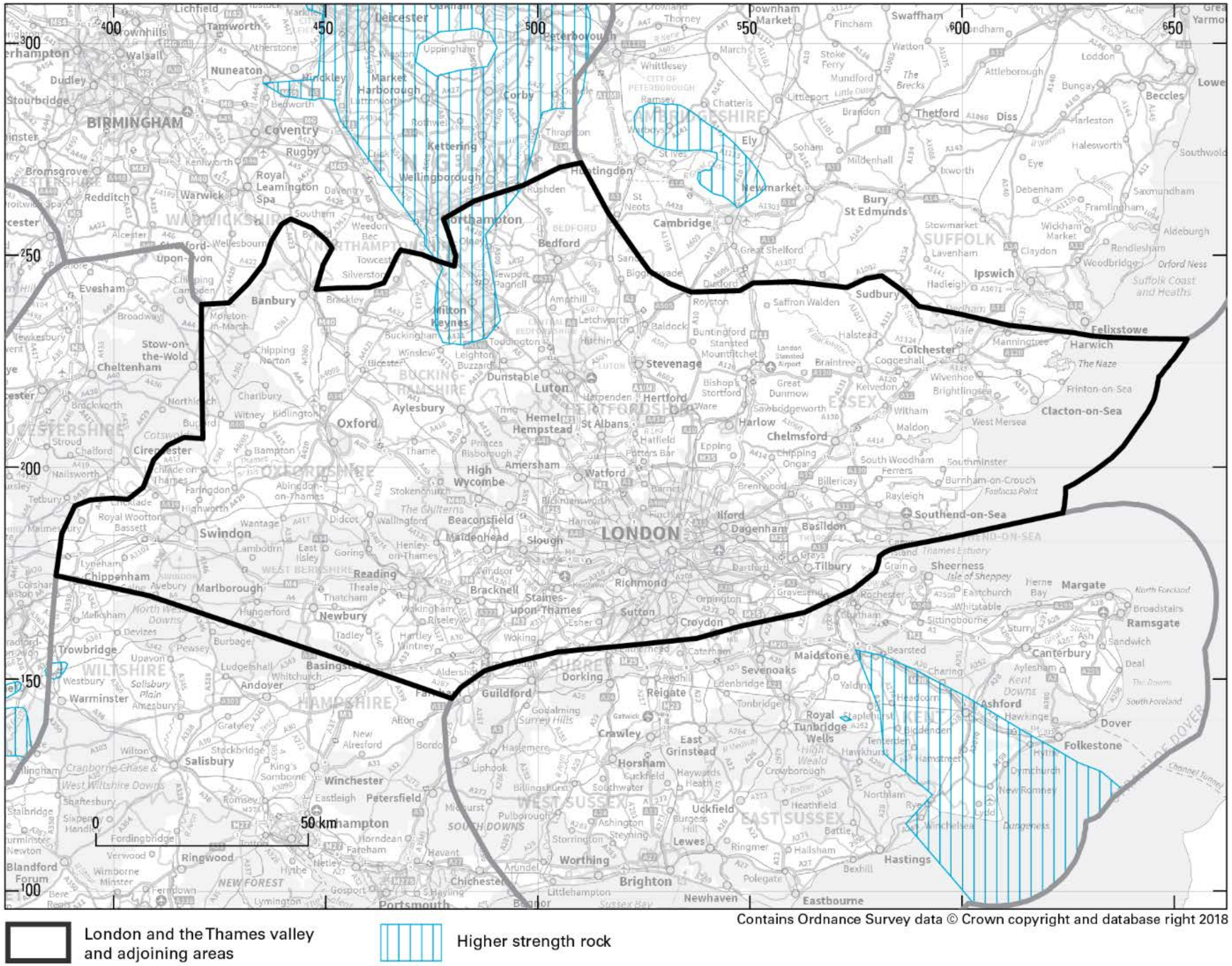


Figure 10 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Thames Valley region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains BGS digital data © British Geological Survey © UKRI 2018.

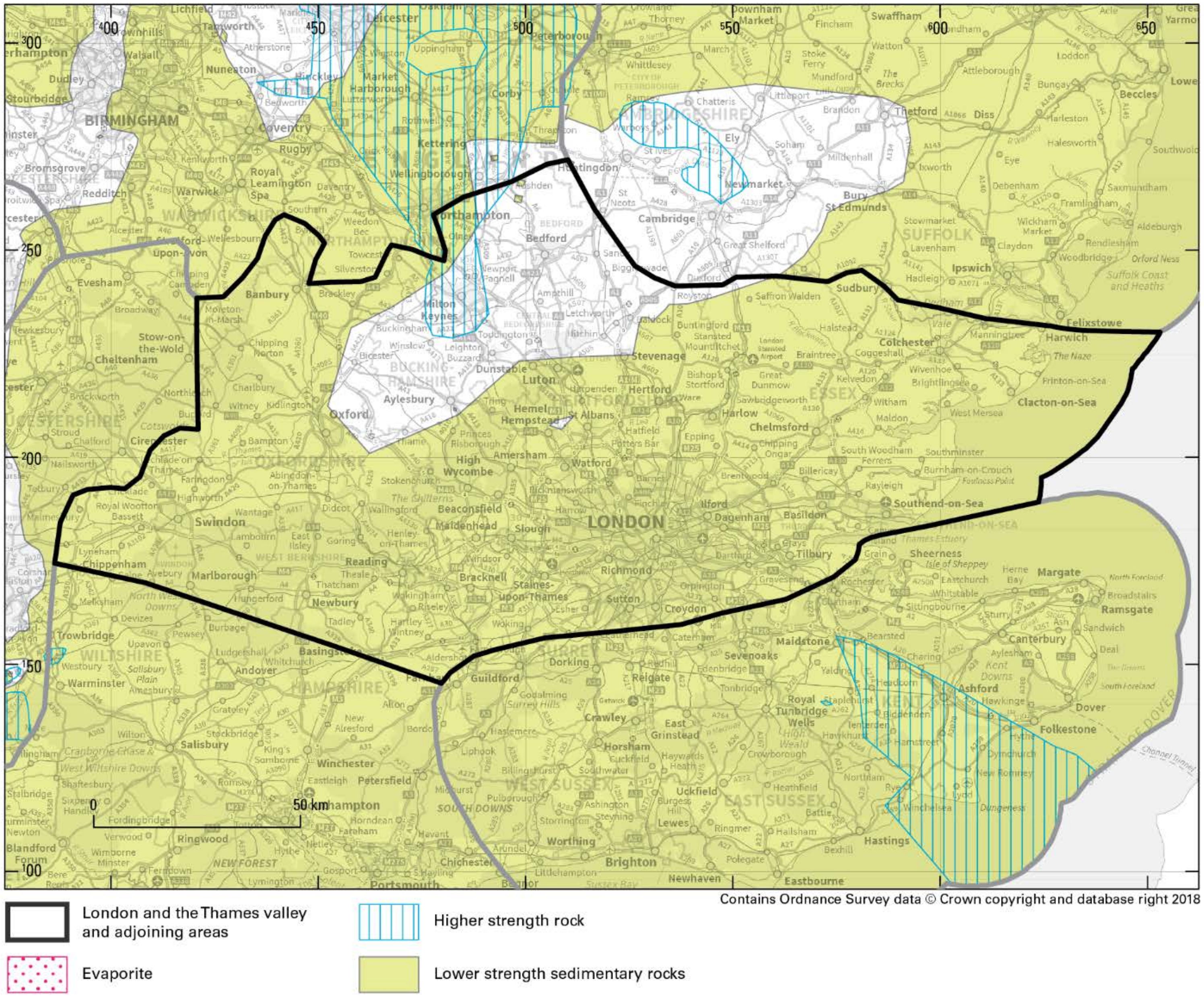


Figure 11 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Thames Valley region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains BGS digital data © British Geological Survey © UKRI 2018.

4.2.1 Younger sedimentary rocks

4.2.1.1 GAULT FORMATION AND UPPER GREENSAND FORMATION (UNDIVIDED) — LSSR

Principal information sources

The Upper Greensand Formation both overlies and is the lateral equivalent of the Gault Formation. The top of the Gault Formation is a diachronous transition from mudstone into Upper Greensand Formation facies (glauconitic sand). At outcrop and in many boreholes the separation of the Gault and Upper Greensand formations is easily made on the basis of their contrasting lithology. However, in the south and west of the region many boreholes do not record the two formations individually and the term Gault Formation and Upper Greensand Formation undivided is used. The Upper Greensand Formation outcrop is continuous from Devizes in the far west to near Dunstable in the north where it thins and wedges out. In the south, from Dorking to near Westerham, the Upper Greensand Formation outcrop forms the southern edge of the region. At outcrop the Upper Greensand Formation reaches a maximum thickness of 25 m near Devizes. It thins to the north and east, dying out altogether near Dunstable (Sumbler, 1996). At depth it occurs west of a line drawn from Dunstable to near Westerham in the south and is absent in boreholes in the London area (for example at Bushey, Hertfordshire and Tottenham Court Road). At outcrop and in the subcrop the Upper Greensand Formation consists of variably cemented quartz sands with glauconite grains and thus is not a PRTI.

The underlying Gault Formation was the earliest Cretaceous formation to extend across the entire London platform. It is up to 100 m thick where it comes to the surface in the upper part of the Thames valley, generally diminishing eastwards at depth to about 60 m, as proved in boreholes at Ware and Fobbing, and only 13 m in Weeley Borehole near Clacton-on-Sea.

From a map in Whittaker (1985) showing the depth to the base of the Chalk, it can be inferred that the Gault and Upper Greensand (undivided) unit occurs within the depth range of interest in a broad swathe that corresponds with the central part of the London basin, and is deepest (the top surface lower than 300 m below Ordnance Datum) beneath east Essex and north Kent and in the Farnborough–Aldershot area west of London (Whittaker, 1985).

Rock type description

The Gault Formation consists mainly of grey mudstone with variable amounts of silt. In general terms it contains more silt-grade silica grains in the west of the region. The basal beds of the Gault are commonly glauconitic, silty and sandy with layers of phosphatic pebbles. The lower part of the formation is dark grey and pyritic whereas the upper part is paler grey and more calcareous. Small greyish buff concretions and nodules rich in calcium phosphate occur locally around fossils and burrows, and there are some seams of bluish black phosphatic pebbles (Sumbler, 1996).

4.2.1.2 WEALDEN GROUP — LSSR

Principal information sources

Rocks of this group occur only in the far south of the region between about Farnham and the River Medway valley, corresponding to the northern edge of the Wessex basin (Figure 4). They were deposited in latest Jurassic and earliest Cretaceous times when the sea retreated from the London platform and the earlier Jurassic cover rocks were subjected to subaerial erosion. The resultant sediment was transported southwards by rivers where it was redeposited to form the Wealden Group sediments. Within the group there are several major cycles of deposition leading to alternating sand and clay-dominated sediments. Only the upper half of the group, the Weald Clay Formation (Hopson et al., 2008), is mostly mudstone and thus constitutes a PRTI; the lower half of the group, known informally as 'Hastings Beds', is dominated by sand and where recognised can be omitted from the PRTI. These two main component units of the Wealden Group are well known from geological surveys and numerous exposures in the Weald of Kent south of the present region (Hopson et al., 2008; Worssam, 1978) but in the Thames Valley region the Wealden Group does not crop out. Several deep boreholes in the southern part of the region (for example Warlingham and Tatsfield (see Sumbler, 1996)) penetrate the Wealden Group succession, though do not provide sufficient information to enable the group to be subdivided.

The subcrop, as inferred from the NGS3D model, lies south of a line from Farnham to the River Medway valley and is entirely within the depth range of interest. North of this the Wealden Group PRTI thins and is cut out against the London platform, the top truncated beneath the Lower Greensand. The location of the northern edge of the subcrop is not well constrained as there are few boreholes. Evidence from these boreholes shows the thickness increases southwards. For example no Weald Clay is present in central London; it is 102.7 m thick in Knockholt Borehole near Croydon and at least 233 m thick near Dorking in Brockham Borehole.

Rock type description

The Weald Clay Formation is composed dominantly of grey thinly bedded mudstone with subordinate siltstones and fine-grained sandstones, some of them calcareous, with shelly limestone and clay ironstone (Worssam, 1978).

4.2.1.3 ANCHOLME GROUP

Principal information sources

The succession in this group is largely mudstone dominated and includes several units that are identified as PRTIs: namely the Kimmeridge Clay Formation, Ampthill Clay Formation, West Walton Formation, Oxford Clay Formation and Kellaways Formation.

This entire Ancholme Group sequence is up to about 180 m thick in this region (see for example Maddle Farm Borehole near Lamborne and Knockholt Borehole near Orpington). It was deposited during a marine transgression that began in the Mid Jurassic and continued through to the Late Jurassic. Although interrupted by minor periods of regression and erosion throughout this period there was generally deepening water around the margin of the London platform (Figure 4), and mud deposition. At times the platform may have been entirely submerged but it remained an area of reduced subsidence compared to the adjacent edges of the East Midlands shelf and Wessex basin (Figure 4). The main hiatus in mud deposition took place during the early part of the Late Jurassic (late Oxfordian). It reduced the amount of clastic material carried into the sea enabling coral growth and carbonate deposition on the margin of the London platform. At this time an interbedded sequence of mudstone, limestone and calcareous sandstone, the Corallian Group, was laid down. On account of the low proportion of mudstone the Corallian Group is not regarded as a PRTI in this region.

The Corallian Group lies between the Kimmeridge Clay and the Oxford Clay formations (both of these are PRTIs), and intercalates with mudstone of the West Walton Formation (a PRTI) at outcrop in the area between Calne in the far south-west of the region and between Oxford and Aylesbury (where it is not in the depth range of interest). North and east from Aylesbury the Corallian Group is not present. The Corallian Group is up to about 35 m thick at outcrop in the west of the region where boreholes prove 17 m at Aston Tirrold between Newbury and Oxford, 53 m at Kingsclere south-west of Newbury, and 46 m at Warlingham near Croydon. The subcrop distribution extends across the western half of the region as far as Reading and along the southern margin of the region, a slightly smaller area than the Ancholme Group subcrop on Figure 12.

The subcrop of the Ancholme Group (Figure 12), based on borehole data, is west and south of a line drawn from the northern boundary of the region through Hitchin to west London and then turning eastwards approximately along the foot of the North Downs through Croydon towards Rochester. The area of subcrop within the depth of interest occupies a tract approximately encompassing Princes Risborough, Tring and Marlborough and Didcot, and then eastwards encompassing Reading, Woking and Croydon.

The main mudstone-dominated formations that constitute the Ancholme Group are readily identified at outcrop, in relatively recent cored boreholes and in good quality wireline logs. However, information from many of the deeper boreholes in the region is of insufficient quality to discriminate the individual formations with certainty. For this reason the NGS3D model has grouped several of the formations in different places, leading to PRTIs encompassing:

- Kimmeridge Clay Formation
- Ampthill and Kimmeridge Clay formations (undivided)
- West Walton, Ampthill Clay and Kimmeridge Clay formations (undivided)
- Kellaways and Oxford Clay formations (undivided)

In the following paragraphs the characteristics of each formation are described separately and the distribution of the individual and, where appropriate, combined formations is described.

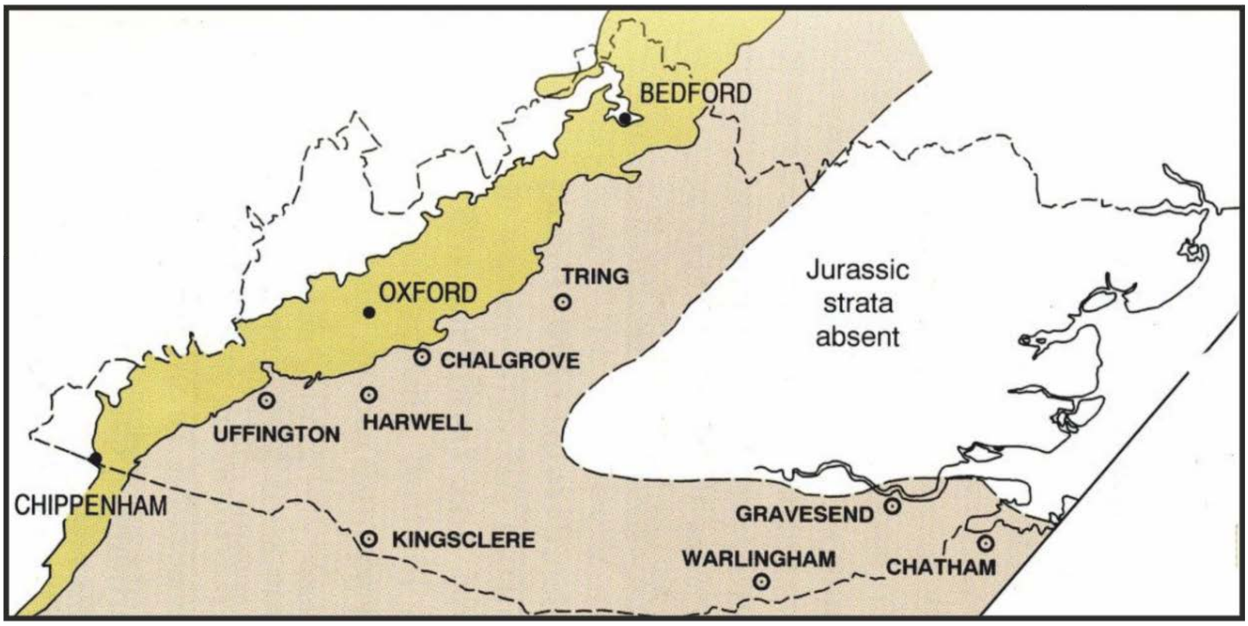


Figure 12 Distribution of Jurassic rocks in the Thames Valley region. Green colour indicates outcrop of the Ancholme Group; grey colour indicates the extent of Jurassic rocks at depth which also corresponds approximately to the extent of the Ancholme Group (which here constitutes almost the entire thickness of Jurassic rocks). From Sumbler, 1996; see also Lee et al., 2015).

KIMMERIDGE CLAY FORMATION — LSSR

Principal information sources

Deposition of the Kimmeridge Clay Formation was influenced by the deepening of the East Midlands shelf and the Wessex basin (Figure 4) when the coastline moved further onto the London platform than at any time during the Jurassic and Triassic.

This formation is known from outcrops in a narrow strip from near Chippenham in the far south-west of the region to near Leighton Buzzard. North-east from here it is cut out by the unconformity beneath the Cretaceous succession. The thickness at outcrop in the north of this tract is up to 50 m. South-westwards it increases to 102 m proved at depth in a borehole at Swindon (Sumbler, 1996). This thickening continues towards the Wessex basin (Figure 4) with about 280 m in Kingsclere Borehole, and more than 200 m in Warlingham Borehole in which a fault cuts out the lower part of the formation (Cope, 2006). Within the depth range of interest, the unit identified as Kimmeridge Clay Formation in the NGS3D model occurs in a narrow east–west tract from Orpington to Newbury.

Rock type description

The Kimmeridge Clay Formation is composed mainly of mudstone ranging from pale to dark grey largely depending on the calcium carbonate content. Brownish grey kerogen-rich fissile mudstone beds (known as ‘oil shale’) occur at some levels. Pyrite is present in fossils, replacing burrow fills and finely disseminated, and some beds mainly in the lower part of the formation contain phosphatic pebbles (Lee et al., 2015). Subordinate beds of silty mudstone, siltstone and muddy limestone are present also and there are widespread cementstone nodule beds. The succession is well known in the large pits near Oxford and Aylesbury where the Kimmeridge Clay Formation was extracted for brickmaking. In this area sandstone and siltstone beds occur widely in the top part of the formation. They are typical of the formation on the London platform and its margins but are absent from the thicker basinal sequences, particularly of the Wessex basin (Figure 4).

Ampthill Clay Formation — LSSR

Principal information sources

This Formation is not identified individually at subcrop in the NGS3D model, in which it is combined with the Kimmeridge Clay Formation. The combined unit is in the depth range of interest in the area around Lamborne and Didcot and northwards to Thame (see for example Welford Park Lane Borehole, near Lamborne).

The Ampthill Clay Formation crops out along the north-west margin of the region between Bedford and Chippenham although exposures are uncommon and the succession is not well known. Only in the past 20 years or so has the formation been more widely identified at outcrop (Sumbler, 1996). In several places it has been eroded away by erosion at the base of the overlying Early Cretaceous Woburn Sands Formation. The thickness at outcrop is estimated at around 13 to 20 m although it is locally less than this, for example east of Oxford (Sumbler, 1996). The extent within the depth range of interest is uncertain but is likely to be similar to the Kimmeridge Clay Formation.

Rock type description

The Ampthill Clay consists of medium to dark grey mudstone, silty mudstone and pale grey calcareous mudstone. Hard nodules of carbonate mudstone occur at some horizons. In the Ampthill area in north of the region the formation is generally clay rich (Barron et al., 2015) whereas in the south-west towards Swindon there is likely to be a greater proportion of silt and with some ferruginous iron-cemented beds (Sumbler, 1996).

West Walton Formation — LSSR

Principal information sources

The West Walton Formation is most complete in the north-east of the region where up to 15 m occurs. Southwards from Oxford the upper part of the formation passes into the limestone-dominated Corallian Group. It is poorly known in the subcrop and hence has not been separately subdivided in the NGS3D model, being combined with the Ampthill and Kimmeridge Clay formations. The maximum thickness is 20 m around Oxford, but generally 15 m are present (Sumbler, 1996).

In the depth range of interest the combined unit of West Walton, Ampthill Clay and Kimmeridge Clay formations is inferred to occur in the area around Princes Risborough and Tring although the West Walton Formation is not identified in any boreholes in this area.

Rock type description

The succession consists of alternating calcareous mudstone and silty mudstone with carbonate mudstone and siltstone nodules. In the Oxford area there are thicker dark grey mudstones containing plant debris, and sand beds increase in number further south as the formation passes into the Corallian Group.

Oxford Clay Formation — LSSR

Principal information sources

The Oxford Clay Formation is well documented in exposures and shallow boreholes mainly on account of its widespread exploitation for brickmaking around Oxford. In the Oxford area and to the north-east, 65 to 75 m is present. South-westwards from Oxford the formation may be up to 150 m thick where it thickens into the Worcester basin (Figure 4) but its extent on the London platform is imprecisely known (Sumbler, 1996) and is generalised as part of the Ancholme Group distribution map in Figure 12. It also extends along the southern margin of the region where there are 96 m and 97 m in Kingsclere and Warlingham boreholes respectively although it is likely that these thicknesses include also the overlying West Walton Formation.

The Oxford Clay Formation occurs within the depth range of interest in a broad tract including Luton, Beaconsfield, Tring, Didcot, Lamborne and Marlborough, and a further narrow tract in the far south of the region that includes Aldershot, Croydon and Gravesend.

Rock type description

The upper third of the Oxford Clay formation is pale grey, blocky calcareous mudstone with thin beds of carbonaceous dark grey mudstone and calcareous siltstone. The middle part is predominantly pale to medium grey, variably silty calcareous mudstone with beds of calcareous siltstone up to 0.3 m thick. The lowest third of the formation comprises brownish grey fissile, organic rich shelly mudstone with subordinate beds of pale to medium grey blocky mudstone and bands of cemented calcareous mudstone.

KELLAWAYS FORMATION — LSSR

Principal information sources

This is the lowest part of the Ancholme Group. The upper part of the Kellaways Formation, directly below the Oxford Clay, is dominantly sandstones and calcareous sandstones (Kellaways Sand Member) generally less than 5 m thick. Its extent at depth is not known. The lower part of the Kellaways Formation, known as the Kellaways Clay Member forms the remaining thickness of Kellaways Formation.

The Kellaways Formation crops out between Bedford, where it is less than 10 m thick, and Chippenham in the south-west of the region where 25 m occurs. The thickening in this area is thought to be due to the influence of faults at the margin of the Worcester basin (Figure 4) (Sumbler, 1996). Down dip the Kellaways Formation is identified for example in boreholes at Kingsclere (9 m) and Warlingham (5 m) but in other boreholes it is included with the Oxford Clay Formation. The distribution in the depth range of interest is likely to be the same as that for the Oxford Clay: a broad tract including Luton, Beaconsfield, Tring, Didcot, Lamborne and Marlborough, and a narrow tract in the far south of the region including Aldershot, Croydon and Gravesend.

Rock type description

The Kellaways Formation consists of an upper unit composed dominantly of sand and sandstone (the Kellaways Sand Member) and a lower unit (Kellaways Clay Member) dominated by mudstones (Sumbler, 1996). The lowest part consists of dark grey shaly and silty mudstone with phosphatic nodules. The upper, and thicker, part of the Kellaways Clay is pale to medium grey sandy and silty mudstone with thin beds of muddy sandstone and cementstone nodules. This particular part of the succession occurs only near Chippenham where it is not within the depth range of interest.

4.2.1.4 LIAS GROUP — LSSR

Principal information sources

In Early Jurassic times the London platform remained emergent or was a shoal area. In basins to the west and south of the platform a substantial thickness of mud-dominated sediment of the Lias Group accumulated, and a thinner succession was deposited on the East Midlands shelf to the north (see Figure 4) (Sumbler, 1996).

The Lias Group as a whole consists of an upper unit of mudstone (Whitby Formation) (Cox et al., 1999), a middle unit dominated by sandstone and ferruginous limestone (Dyrham and Marlstone Rock formations up to 35 m thick), and a lower unit of dominantly mudstone (Charmouth Mudstone Formation) overlying mudstone with persistent limestone beds (Blue Lias Formation).

The Lias Group occurs within the depth range of interest in an area encompassing Swindon, Newbury and Chippenham where it is around 200 to 400 m thick (Figure 14), with a maximum of 454 m proved in Cooles Farm Borehole. On the basis of the Stowell Park Borehole (Sumbler, 1996) 45 km east of Oxford and 12 km east of the edge of the present region it seems likely that all the component formations of the Lias Group occur in this area although there is no confirming evidence. Regional evidence (Sumbler, 1996) suggests that the proportion of limestone beds in the lower part of the sequence (the Blue Lias Formation) is likely to decrease eastwards in this area. Also in this area, the Whitby Mudstone, Marlstone Rock and Dyrham formations in the top half of the succession may be removed by erosion particularly in the eastern part of the area.

The Lias Group subcrop from Newbury eastwards to Tilbury forms a wedge that increases in thickness southwards towards the margin of the region, as illustrated by the Normandy 1 and Knockholt boreholes, to a maximum of 201.5 m in Warlingham Borehole. However, only the northern (thinner) portion of the wedge is within the depth range of interest, where the Lias Group is generally less than 100 m thick. The remainder of the wedge is below the depth range of interest.

Rock type description

The upper part of the Lias Group (Whitby Mudstone Formation) is, at most, 100 m thick and probably thins eastwards within the depth range of interest. It consists of silty mudstone with thin beds of limestone and thin conglomeratic beds with reworked limestone concretions. In the wedge of Lower Lias along the southern margin of the region, the uppermost beds of the Whitby Mudstone Formation are ferruginous.

The Dyrham and Marlstone Rock formations, underlying the Whitby Mudstone, comprise mainly mudstone and fine-grained sandstone with ironstone nodules and ferruginous limestone within the depth of interest in the western area (as proved in Stowell Park Borehole), and largely limestone in the southern area (as proved in Warlingham Borehole).

The thickest and most complete sequence of the Lower Lias within the depth range of interest is dominated by mudstone. It comprises Charmouth Mudstone, dominantly of grey calcareous silty mudstone overlying an interbedded limestone–mudstone sequence up to about 40 m thick (the Blue Lias Formation). Within the Blue Lias Formation, limestone frequency decreases towards the north and west from the areas within the depth of interest.

There is insufficient evidence to quantify lateral changes in the lithology of the Lias Group in the region, although in general terms, the number of limestone beds decrease towards the northern and eastern margins of the subcrop (Figure 13).

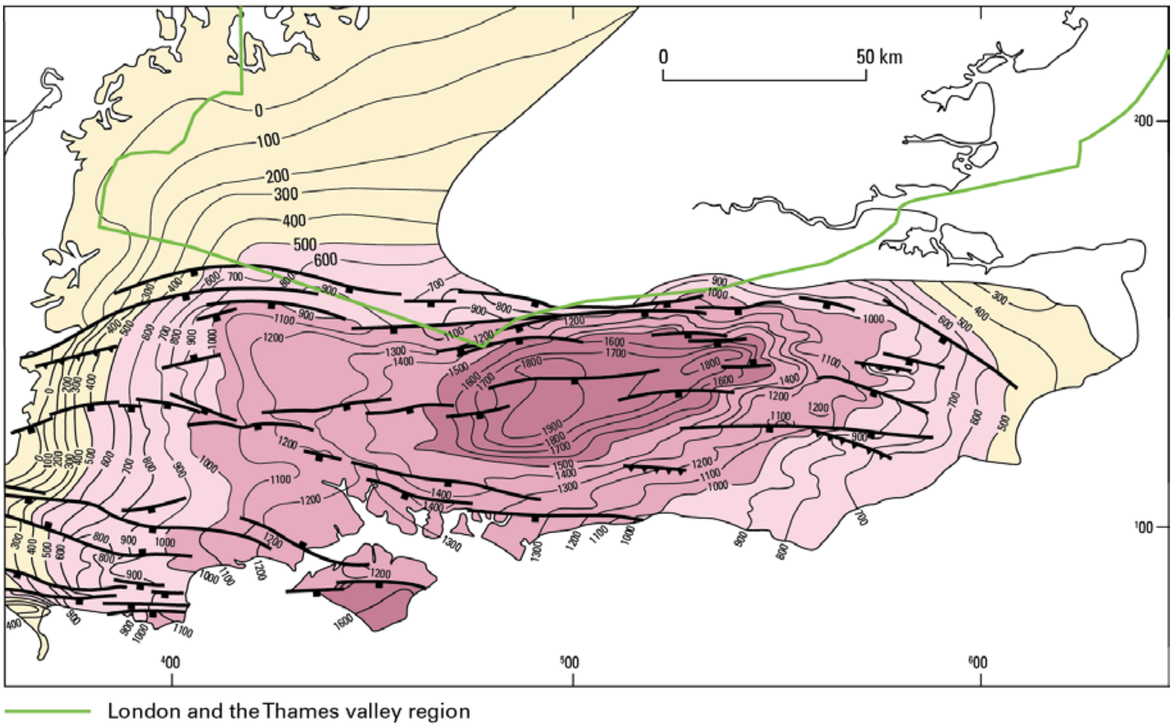


Figure 13 Depth to top of the Lias Group in metres (from Whittaker 1985). British Geological Survey © UKRI 2018

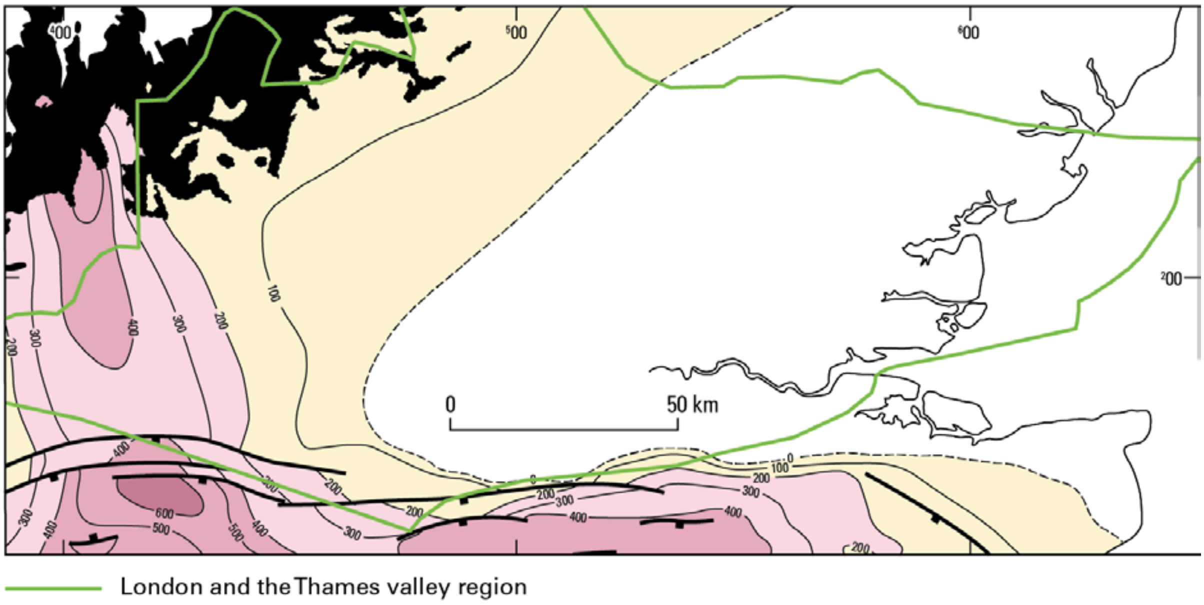


Figure 14 Lias Group isopachytes in metres (from Whittaker, 1985). British Geological Survey © UKRI 2018

4.2.1.5 MERCIA MUDSTONE GROUP AND PENARTH GROUP — LSSR

Principal information sources

The Mercia Mudstone Group and overlying Penarth Group are modelled together (ie undivided) in NGS3D.

Subsidence in the Worcester basin and the western part of the Wessex basin during the Triassic allowed a thick accumulation of Mercia Mudstone Group to build up. In the Swindon–Malmesbury area, in the far west of the region along the axis of the Worcester basin, 400 m of mudstone were laid down (Figure 15) (see for example Cooles Farm Borehole). Other boreholes and geophysical evidence show a marked thinning of the Mercia Mudstone onto the London platform, perhaps controlled by syndepositional fault movement. Much of the Mercia Mudstone subcrop, encompassing Banbury, Oxford, Swindon, Reading and Newbury, is within the depth range of interest, although in the far west from Swindon to Chippenham it is largely below the depth range of interest (Figure 16).

The Penarth Group unconformably overlies the Mercia Mudstone, with a comparable distribution and extent, thinning onto the London Platform (Figure 16).

Rock type description

The Mercia Mudstone Group is almost entirely reddish brown mudstone and siltstone. The topmost beds, up to 10 m thick, consist of greenish grey mudstones. Beds of laminated silty mudstone up to 0.5 m thick occur at intervals. Anhydrite and gypsum occur as layers and nodules 100 mm or less in diameter at many horizons, notably in the upper half of the succession (Worssam et al., 1989). There is no evidence of halites in the succession. Thin beds of greenish-grey quartzose sandstone occur sporadically and beds of brown quartzose sandstone and siltstone increase in number in the basal 10 m or so. There are insufficient data to evaluate lateral lithology changes in the Mercia Mudstone of this region, but marginal conglomerates occur around Palaeozoic highs to the west in the Bristol and Gloucester region.

The Penarth Group is most completely developed in the central parts of the Worcester Basin where it is about 20 m thick. The basal part comprises dark grey, shaly mudstone of the Westbury Formation overlain by of pale greenish grey silty mudstones and limestones of the Lilstock Formation.

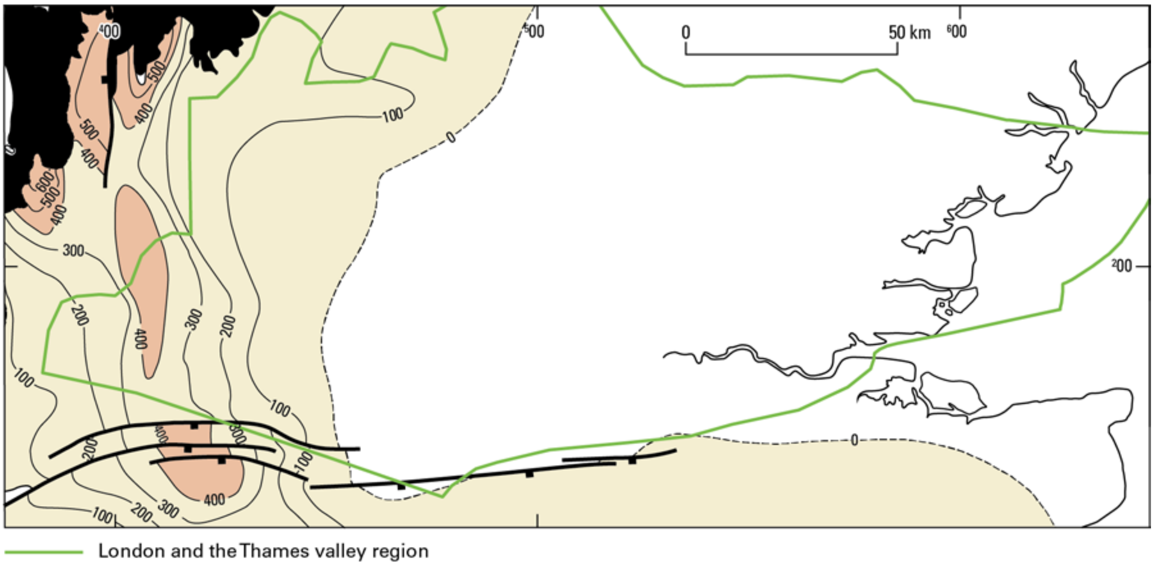


Figure 15 Mercia Mudstone Group isopachytes in metres (from Whittaker, 1985). British Geological Survey © UKRI 2018

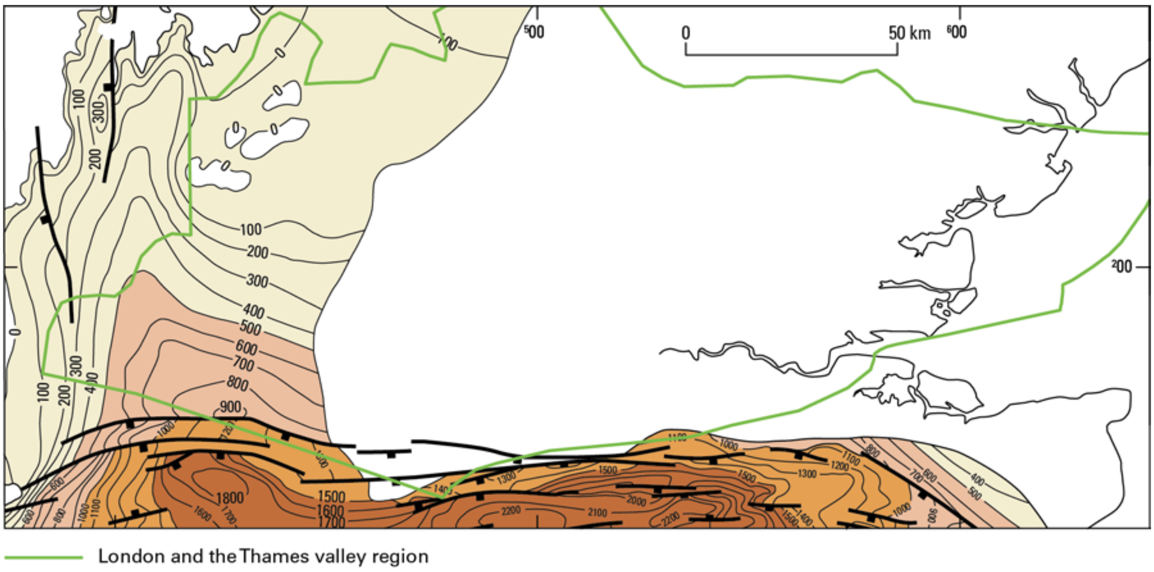


Figure 16 Depth to top of Penarth Group (metres below Ordnance datum) (from Whittaker, 1985). Note the top of the Penarth Group is no more than 20 m above the top of the Mercia Mudstone Group. British Geological Survey © UKRI 2018

4.2.2 Older sedimentary rocks

4.2.2.1 WARWICKSHIRE GROUP — LSSR

Principal information sources and rock type description

This occurs in the west of the region in a tract up to 40 km wide extending from Banbury in the north to the Reading–Newbury area. It lies between about 300 and 1200 m below NGS datum and is therefore mainly within the depth of interest. The tract is generally known as the Oxfordshire and Berkshire coalfield, where the succession in the Warwickshire Group is defined by a number of boreholes drilled for coal exploration (for example Apley Barn and Aston Tirrold).

In the north of the coalfield more than 1000 m are proved, the upper half being dominantly of mudstone and siltstone with sandstones (generally 1 to 30 m thick), thin seatearths and thin coals, known as the Grovesend

Formation. The lower half of the Warwickshire Group in the north of the coalfield is dominated by sandstones known as the Pennant Sandstone Formation, that preclude interest as a PRTI. In the south of the coalfield the upper part of the Warwickshire Group is removed by erosion and only the sandstone-dominated part of the succession, unsuitable as a PRTI, is present. The units are undivided in the NGS3D model.

4.2.3 Basement rocks

4.2.3.1 AVALONIAN PROTEROZOIC CRYSTALLINE BASEMENT — HSR

The basement rocks in the region generally lie at more than 1.5 km below NGS datum in parts of the west and south of the region whereas in central and eastern parts they are at much shallower depth, forming the London platform.

The great majority of these basement rocks consist of Cambrian, Ordovician, Silurian and Devonian sedimentary rocks (Figure 17). These early Palaeozoic sedimentary rocks lie outside established cleavage belts (Acadian and Variscan) and it is not known whether the mudstone component of these rocks preserves a pervasive cleavage. Because of this they are not considered to be a PRTI.

However, crystalline basement rocks have been proven in two boreholes in the region. At the bottom of the Fenny Stratford (Bletchley Station) Borehole (see Figure 5) a granitic intrusion was encountered at a depth of 124 m below NGS datum, although it was penetrated only for 1m. Its lateral extent is unknown in detail but the NGS3D model indicates a subcrop within the depth range of interest that extends north towards Bedford and Hitchin. Although proven by borehole, the confidence on their composition and distribution is considered low, they cannot be ruled out at this stage and have been retained as a PRTI.

Basaltic andesite lavas proved in Withycombe Farm Borehole near Banbury in the north-west of the region however predominantly occur below the depth range of interest and are of insufficient volume to be retained as a PRTI.

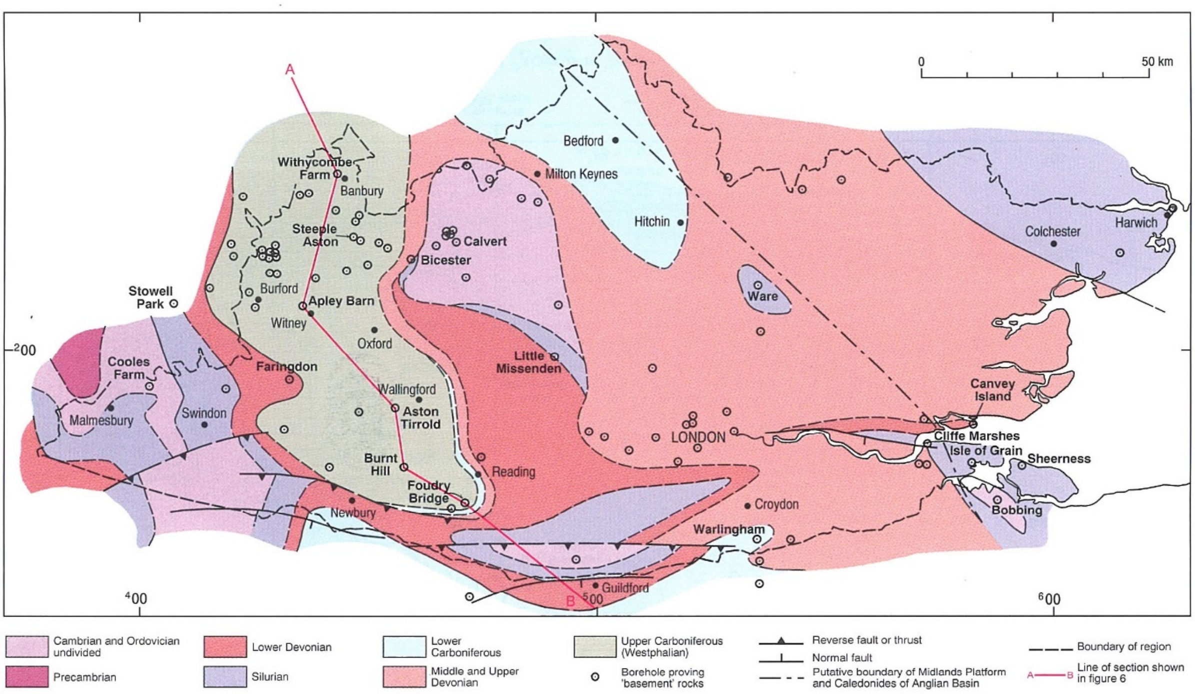


Figure 17 Sketch map showing the distribution of Precambrian and Palaeozoic basement rocks beneath Mesozoic cover in the Thames Valley region. British Geological Survey © UKRI 2018

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

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

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

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

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

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

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

5.2 REGIONAL TECTONIC SETTING

The structural and tectonic evolution of the whole of England, Wales and Northern Ireland is described in Pharaoh and Haslam (2018) and only the events that have contributed to the geological history of the Thames Valley region, and the major rock units that make up its structure are described here.

Structures that developed during four distinct episodes of major structural deformation and mountain building (orogenies) are present in the Thames Valley region. Each orogeny has an associated basement (the rock units deformed and metamorphosed during the orogeny) and a post-orogenic cover sequence (which may be deformed, at least in some areas, by subsequent orogenies).

The geological units seen on the regional geological map of the area date from Jurassic, Cretaceous and Palaeogene times, with the oldest rocks cropping out in the north-west (Pharaoh and Haslam, 2018). However, in much of the area older rocks are encountered at depths of less than 1000 m below NGS datum (Sumbler, 1996; Whittaker, 1985), so it is also important to consider the structure of the pre-Mesozoic basement that lies beneath the cover sequence successions seen at the surface, and the tectonic events that have influenced its formation. The pre-Mesozoic basement of the region can be divided between three terranes, formed in turn during the Avalonian, Caledonian and Variscan orogenies (Ellison et al., 2004; Pharaoh and Haslam, 2018). The subsequent Alpine Orogeny influenced the structure of both the pre-Mesozoic basement and its cover sequence (Pharaoh and Haslam, 2018). The distribution of the Mesozoic and Palaeogene rocks seen at the surface in this region is largely a consequence of earth movements at this time.

The centre and west of the region is underlain by portions of the Charnwood terrane of the Midlands microcraton ((Pharaoh and Haslam, 2018), where Neoproterozoic and early Palaeozoic rocks occur at relatively shallow depths, and which has been relatively tectonically stable during the Phanerozoic. The eastern edge of the Charnwood terrane follows an approximately known north-west to south-east line passing near Bedford, and through south-west Essex, towards the Isle of Grain in coastal north Kent. Structural trends within the microcraton are complex, reflecting deformation during the Avalonian Orogeny in late Precambrian times (Pharaoh and Haslam, 2018). However, according to the UK3D geological model, within nearly all of the Thames Valley region, the Neoproterozoic rocks of the Charnwood terrane occur only at depths greater than 1000 m below NGS datum; the exception is in a small area around Milton Keynes, very close to the northern edge of the region. Otherwise, only the early Palaeozoic cover sequence, which is thought not to be tightly folded, occurs within the depth range of interest.

To the east of the Midlands microcraton, the region is underlain by part of a fold belt formed during the Acadian phase of the Caledonian Orogeny with early Palaeozoic sequences that are much thicker than those on the microcraton (Pharaoh and Haslam, 2018). The dominant structural trends in this terrane are north-west to south-east, ranging to east–west (Lee et al., 1990; Pharaoh et al., 1987a). This fold belt is known as the eastern Caledonides (or the concealed Caledonides of eastern England (Pharaoh et al., 1987a)). Sparse boreholes show the Silurian sediments of this region to be folded and cleaved, in contrast to their time equivalents within the Midlands microcraton (Lee et al., 1990; Pharaoh et al., 1987a). Together, the Midlands microcraton and the eastern Caledonides subsequently acted as a major, relatively stable, structural block, the Anglo–Brabant massif (Pharaoh and Haslam, 2018), which extends east from central England into the nearer parts of continental Europe. The Anglo–Brabant massif acted as a relatively stable area through the Carboniferous, with the development of the Oxfordshire and Berkshire coalfields, which occur at depth in the south-west of the region. The presence of the coalfield basins can be attributed to compensatory extension and subsidence during the early stages of Variscan deformation.

The south of the region includes the northern edge of a Variscan fold belt, marking the northern extent of the Variscan terrane, formed in late Palaeozoic times. Its structure is dominated by east–west-trending, northwards-verging folds and thrusts, presumably comparable to those seen at the surface in parts of Devon and Cornwall. Deformation started in the mid Carboniferous, prior to deposition of the coal-bearing strata of the region, and continued into latest Carboniferous or early Permian times, whereby the coalfields were folded and tectonically truncated from the south (Sumbler, 1996). Steeply dipping late Carboniferous strata were intersected in the Welford Park Station Borehole, on the south-west margin of the Oxfordshire coalfield (Aldiss et al., 2004). The Variscan fold belt was the site of basin subsidence during the Mesozoic and basin inversion during the Palaeogene, whereas the Anglo–Brabant massif remained relatively stable during that time.

Folded and thrust basement rocks of the Variscan terrane extend only a short distance into the southern fringes of the London and Thames Valley region, where they are found at depths of more than 500 m below sea level (Ellison et al., 2004; Sumbler, 1996). The exact position of the northern extent of Variscan thin-skinned tectonic structures, known as the Variscan front, is uncertain (Shackleton, 1984). Conventional interpretations place it close to, and approximately parallel with, the southern edge of the Thames Valley region but it is possible that it extends further north in places, for example to encompass a major negative gravity anomaly in the south of London (Aldiss et al., 2014; Busby and Smith, 2001; Ellison et al., 2004).

The rocks corresponding to that anomaly, probably a thick sequence of late Palaeozoic strata, are apparently separated from the Midlands microcraton by a zone of north-east to south-west-trending basement faults, of unknown displacement, as indicated by linear features in the local gravity field (Aldiss et al., 2014; Ellison et al., 2004). This basin margin fault zone seems to have been reactivated in Palaeogene times to form the Wimbledon–Greenwich fault zone. It is likely that other high-angle Variscan faulting occurred north of the Variscan front, and this may also have been reactivated during the Mesozoic and Cenozoic. Within the Variscan fold belt, and at its margins, Variscan faulting is typically compressional and so is commonly reversed, whereas Mesozoic faulting was extensional and normal. Cenozoic faulting was again under a compressional regime and so includes some reversed inverted elements. To the north of the fold belt, in particular, some high-angle faults may have been transpressional, developing significant lateral offsets.

Regional folding of Variscan age also occurred to the north of the Variscan front, most evidently in the preservation of the Carboniferous strata of Oxfordshire and Berkshire in a north–south-oriented basinal structure. Other folds in the Palaeozoic sequences, such as the possible Streatham Anticline (which is inferred to lie beneath the Mesozoic strata of south-west London) could have formed at this time (Ellison et al., 2004).

Much of the region lies within the London platform, a part of the Anglo–Brabant massif that remained relatively stable during the Mesozoic. As shown in the UK3D geological model, basement rocks (of early Palaeozoic age or older) occur here at less than 500 m depth, and in the north of the region, they are present within 150 m of the ground surface (Sumbler, 1996).

During most of the Mesozoic only relatively thin sedimentary sequences were deposited over the London platform, or were not deposited at all, or were subsequently removed by erosion. There is some evidence of syndepositional normal faulting during the Jurassic, notably in an east–west fault zone just east of London (including the Cliffe Fault) (Ellison et al., 2004). Much thicker Mesozoic successions are present in the west of the region, in the Worcestershire basin of the Bristol and Gloucester region, and to the south, in the Wessex basin (including its eastwards extension, the Weald basin of the Wealden region), in areas of crustal extension and subsidence (Sumbler, 1996). The faults at the northern margin of the Weald basin, which are close to the southern edge of the Thames Valley region, are thought to have formed by reactivation of underlying Variscan thrusts (Chadwick, 1986; 1993). Only the Chalk and the immediately underlying Gault Formation were deposited as continuous post-rifting layers across the London platform, although their successions are markedly thinner there than to the south, in the Weald basin (Aldiss, 2013; Ellison et al., 2004).

During the Late Cretaceous, regional compression led to the reactivation of basement faults and the onset of basin inversion in the southern North Sea and in the Weald basin. This early phase of movement of the Alpine Orogeny, continuing into the Paleocene (the early part of the Palaeogene), led to gentle folding and erosion of the Chalk in the London area (Ellison et al., 2004; Mortimore and Pomerol, 1987).

Later on during the Palaeogene, crustal movements related to the opening of the North Atlantic Ocean were accompanied by uplift across the British Isles, with tilting towards the south-east. This led to the formation of a series of Palaeogene sedimentary basins across the United Kingdom, and was followed by regional subsidence and marine transgression. As a consequence, the southern part of the North Sea basin extended south-westwards: it was at times connected with Palaeogene basins in the English Channel and Western Approaches (Cameron et al., 1992). Parts of the successions deposited in these basins are now found onshore in the London basin and East Anglia, and also in Hampshire. It is possible that the extent of Palaeogene deposits in the London basin is partly controlled by minor contemporary faulting (Aldiss, 2015; King, 2006).

A second phase of tectonic activity (the major phase of the Alpine Orogeny) affected the region in Late Oligocene to Mid Miocene times, when the Mesozoic Weald basin was inverted (changed from being an area of subsidence and deposition to one of uplift), so creating the syncline-like structure known as the London basin, dividing it from what now appears to be a separate Palaeogene basin in the Hampshire region (Cameron et al., 1992; King, 2006). Extensional basin margin faults were reactivated and reversed as part of these events, and are marked at the surface by features such as the Hog’s Back ridge of western Surrey (Chadwick, 1986; 1993). These structures are described in more detail as part of the structure of the Hampshire and Wealden regions. Smaller, monoclinal folds within the London basin, such as the Greenwich Anticline, were formed by movements along underlying basement faults penetrating the southern part of the London platform (Ellison et al., 2004).

5.3 MAJOR FAULTS

5.3.1 General patterns of faulting

As shown on the published geological maps, faults in the Thames Valley region mostly trend either approximately north-east to south-west or north-west to south-east, although other orientations occur. It is likely, considering their orientation relative to the regional compression during the Alpine Orogeny, that elements of strike-slip occurred on these faults, in addition to elements of dip-slip motion.

The largest faults that have been mapped in the London area are the *en échelon* strands of the Wimbledon–Greenwich fault zone, with maximum recognised downthrows of 30 m to the north (Aldiss et al., 2014; Ellison et al., 2004). The close association of these faults with narrow asymmetrical folds such as the Greenwich Anticline, into which the Greenwich Fault passes, suggests that their formation included components of reverse movement. The inferred regional stress regime, with north–south compression, suggests that sinistral strike-slip movements might have occurred as well. Faults elsewhere in the region are described as being ‘near-vertical’ (near Reading) (Mathers and Smith, 2000), ‘mostly normal’ or ‘apparently normal’ in the Thame (Horton et al., 1995), Chipping Norton (Horton et al., 1987) and Bedford districts (Barron et al., 2010), or there is insufficient definition of their orientation and sense of displacement to be able to determine their type. Moreover, there is evidence that the Great Milton Fault (part of the Wheatley fault zone near Thame in the north-west of the region) has undergone both normal and reversed movement at different times (Horton et al., 1995), and it is possible that many other faults in the region have also been activated at various times under differing tectonic regimes. Proven displacements of faults in surface strata rarely exceed about 25 m.

Aldiss (2013) has argued that faulting is widespread and common in the London area, and in the south-east of England in general, and that it is under-represented on current geological maps. It is noticeable that most of the mapped faults in the Thames Valley region occur in the north-west, in predominantly rural areas underlain by Jurassic and Early Cretaceous strata composed of a variety of contrasting rock types. The apparent paucity of mapped faults elsewhere is likely to be a consequence of the difficulty of recognising faults in uniform bedrock units, and in areas with extensive superficial deposits (including anthropogenic deposits) or built structures (Aldiss, 2013). It can be assumed that such unrecognised faults have similar orientations and displacements to those that are shown on the geological maps but they might also include faults with significant strike-slip displacements.

Even so, it is very probable that no fault zones that displace strata at or close to the ground surface within this region have vertical displacements of 200 m or more. Even where the bedrock is predominantly composed of thick and homogeneous units, or where it is obscured by superficial deposits, such displacements would be expected to be readily apparent during conventional geological surveying. However, fault zones with large vertical or lateral displacements are likely to be present in the pre-Mesozoic basement, possibly in some locations where no surface faulting exists, or none has been recognised. Several basement fault zones are thought to lie within, or very close to, the Thames Valley region.

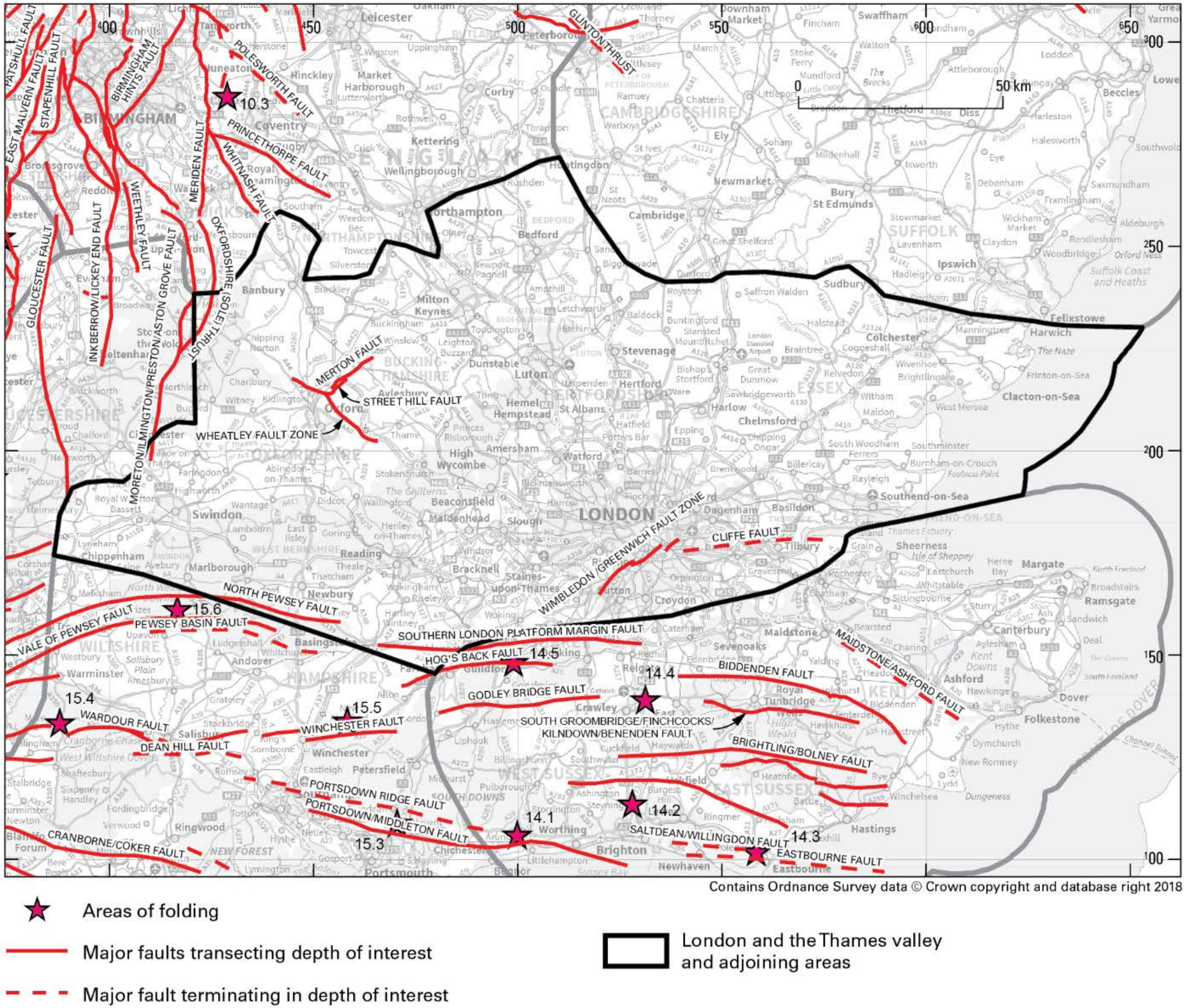


Figure 18 Map of the major faults and areas of folding in the Thames Valley region. No areas of intense folding have been identified. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

5.3.1.1 Cliffe Fault

A major down-to-south normal fault oriented approximately east–west has been identified in the pre-Mesozoic basement beneath the lower reaches of the River Thames, extending from south London eastwards to the Isle of Grain in coastal northern Kent. It forms the northern side of a graben in which the Oxford Clay Formation (of Jurassic age) is preserved, faulted against Silurian or Devonian sediments at a depth of only about 300 m below sea level. This graben formed in Late Jurassic or Early Cretaceous times (Ellison et al., 2004; Owen, 1971; Sumbler, 1996). A similar, but apparently smaller, graben structure beneath central London juxtaposes strata of the Great Oolite Group with the Devonian, at a little more than 300 m below sea level (Ellison et al., 2004). The thickness of the Jurassic sequences in this area is poorly known and so the displacement on the graben-forming faults cannot be estimated, but they are evidently long-lived structures of some significance.

The formation of gentle periclinal folds in the Chalk and Palaeogene deposits close to the River Thames east of London, apparent from their mapped outcrop patterns, can be attributed to movements on the Cliffe Fault, or others nearby and parallel to it, during the Late Cretaceous or Cenozoic. However, there is no evidence for large fault displacements in the post-Jurassic successions in this area.

5.3.1.2 Wimbledon–Greenwich fault zone

The largest faults that have been mapped at the surface in the London area are the *en échelon* strands of the Wimbledon, Streatham and Greenwich faults. A coincident lineament in the regional Bouguer gravity anomalies, and others parallel to it, have been suggested to mark faults active during Mesozoic deposition. This zone of lineaments separates an area to the north with very broad folding from that to the south which is characterised by numerous periclines (Ellison et al., 2004). It is assumed that the lineaments mark large north-east to south-west normal faults at depth in the pre-Mesozoic basement, forming a fault zone inferred to separate the Midlands microcraton (to the north-west) from thick sequences of late Palaeozoic strata under south London (Aldiss et al., 2014; Ellison et al., 2004). Latest Silurian strata found in the Streatham Borehole of south-west London were taken by Ellison et al. (2004) and Sumbler (1996) to mark an anticline in the pre-Mesozoic basement but it also seems possible that this occurrence instead marks an upstanding fault block within this proposed fault zone. There is no evidence for the amount of displacement on these inferred faults, but in the Palaeozoic rocks (at depths greater than about 300 m below sea level) it is likely to be relatively large.

5.3.1.3 North Pewsey and Hog's Back faults

A series of *en échelon* fault zones, oriented approximately east–west, occurs close to the southern margin of the region, including the North Pewsey Fault, the Southern London Platform Margin Fault and the Hog's Back Fault. These structures formed along the northern margin of the Weald/Wessex basin and they are described as part of the structure of the Hampshire and of the Wealden regions.

5.3.1.4 Merton and Street Hill faults and the Wheatley fault zone

As mapped at the surface, the Merton Fault is a normal fault downthrown to the north-west, probably with a displacement of less than about 25 m. The UK3D model interprets it as a normal fault downthrown to the south-east, with an inferred maximum displacement of a little more than 500 m. It displaces Silurian strata against Cambro-Ordovician successions, between 200 and 1000 m below NGS datum. The difference in displacement direction at the surface and at depth, if correct, presumably reflects a complex history of fault movement in this area, as noted for the Great Milton Fault (Horton et al., 1995).

About 1 km to the south-east and lying subparallel to the Merton Fault, the Street Hill Fault, a normal fault downthrown to the south-east, has an inferred displacement of more than 600 m within early Palaeozoic sequences at depths greater than 1000 m below NGS datum.

To the south-west, the Street Hill Fault is apparently truncated by elements of the north-west to south-east-trending Wheatley fault zone. This was active during Jurassic and later times. The complex structure and history of movement in this zone suggests that it marks a significant structure in the pre-Mesozoic basement (Horton et al., 1995), although it has not yet been modelled at that depth. The relationship between the faults seen at the surface in this area and the inferred displacements at depth in the basement are discussed further in the section on uncertainty.

5.3.1.5 MORETON–ILMINGTON FAULT

The southern extremity of this fault lies near the western end of the Thames Valley region. It is described in the corresponding report for the Bristol and Gloucester region.

5.4 FOLDING

Folding of the geological units occurring in the Thames Valley region is here described separately for the three basement terranes, and for their cover sequence. Significant folding of heterogeneous rock units is possibly present within the depth range of interest only in the Variscan terrane, but there is insufficient information to delineate areas where this occurs.

In most of the region, the post-Variscan cover sequence dips gently to the south-south-east, typically at less than 2° (Ellison et al., 2004) into the core of the London basin syncline. Regional dips decrease towards the axis of the London basin, where strata typically lie close to horizontal. Only in the southern fringes of the region are regional dips towards the north, typically at less than 3°. The southern side of the London basin displays several very gentle east-north-east-trending periclinal folds, some of which are apparent from the mapped outcrop patterns of the geological units. Although the limbs of these folds generally dip at less than 7° (Ellison et al., 2004), they probably represent movement on larger structures in the basement, reactivated during Alpine earth movements. Asymmetrical folding occurs close to some major faults, in places with steeply dipping strata forming a monocline. These fault-related folds have a tendency to have steeper north-facing limbs, as mentioned in the previous section. The clearest example, which is apparent on the regional geological map, is the Greenwich Anticline, in south-east London. Others are depicted by Ellison et al. (2004).

Folding also occurs in some other parts of the region, for example in the Thame district (Horton et al., 1995), but it is everywhere very gentle.

The sub-Mesozoic basement terranes can all be expected to include zones of complex folding. In the Midlands microcraton, these probably involve rocks similar to the Neoproterozoic volcano-sedimentary successions of Leicestershire, perhaps including igneous intrusions. Within the region, only one borehole (at Withycombe Farm, Oxfordshire, in the extreme north-west) has penetrated the Neoproterozoic, finding volcanic rocks. Structural trends appear from the regional potential fields to be complex. However, according to the NGS3D model, the Neoproterozoic basement of this region occurs only at depths greater than 1000 m below NGS datum, other than in a small area at the northern edge of the region. Strata of the early Palaeozoic cover sequence, which does occur within the depth range of interest, have been found not to be cleaved, and are expected not to be tightly folded. A borehole at Fenny Stratford (Bletchley Station), close to the northern edge of the region, found granitic rock at a depth of only 124 m below NGS datum. This is thought to be Ordovician in age and to intrude the early Palaeozoic cover sequence.

The eastern Caledonide fold belt is thought to comprise thick early Palaeozoic successions that have been tightly folded and cleaved on mainly north-west to south-east trends. According to the NGS3D model, close to London such rocks occur at depths of about 900 m below NGS datum, but appear at progressively shallower levels towards the north-west, and to the north-east, reaching as little as 250 m below NGS datum near Sudbury on the Essex–Suffolk border. However, boreholes that have sampled this terrane suggest that it is dominated by rather uniform mudstones, siltstones and fine sandstones (Woodcock and Pharaoh, 1993), analogous to early Palaeozoic successions in the Southern Uplands and the northern Lake District. Volcanic and plutonic rocks have been found within parts of the eastern Caledonide fold belt, but so far none have been demonstrated to occur within the Thames Valley region (Pharaoh et al., 1987a; 1987b; 1993).

The Variscan terrane, which impinges on the south of the region, includes northward-vergent folds and thrusts, mostly in Devonian and early Carboniferous successions. Little is known about the style of deformation of these rock units as they occur within the Thames Valley region. By analogy with those occurring within the Variscan terrane of south-west England, the basement in the south of the Thames Valley region is likely to include zones of open to tight folding, with thrust dislocations and overturned strata. At Bolney, near Horsham in the adjacent Wealden region, a deep borehole passed through almost 500 m of Devonian strata, mainly mudstones 'with much shearing' and fracturing. Mostly, dips found in this borehole range from 30° to more than 60°, and in some intervals there are small tight folds with dips of 70° in overturned strata (Gallois and Worssam, 1993). It is likely that in the Thames Valley region, rock units in the Variscan terrane are composed mainly of sandstones and mudstones perhaps with some conglomerates or limestones. It is possible that some parts of the Variscan fold belt in the region comprise heterogeneous rock masses with strongly contrasting physical properties, but there is insufficient information to delineate them.

5.5 UNCERTAINTY

As indicated in the preceding account, many aspects of the structure of the Thames Valley region are known only in outline: there is too little information to be confident about many of the details, particularly in the basement.

The composition and structure of the post-Variscan cover sequence is fairly well known from surface geological mapping and shallow borehole evidence. Where they are shown on published geological maps, the outcrop trace of faults is likely to be accurate, in most places probably to within about 100 m of their actual ground position. However, the distribution of faults is likely to be only partially known, as is their inclination, and the amount and direction of their displacement. Knowledge of all these depends on being able to observe offsets of strata, or to be able to infer such offsets with reasonable confidence. Where rock units are homogeneous, or are covered by superficial deposits or occur in urban areas, faults can be very difficult to recognise and to define, other than by detailed three-dimensional modelling of a sufficient density of borehole records (Aldiss, 2013; Aldiss et al., 2012), or by seismic reflection surveys.

For the pre-Mesozoic basement, the situation is considerably worse. Very few seismic reflection surveys have been carried out in the east of the region, especially over the London platform. Knowledge of the deep structure is revealed only by the regional gravity and aeromagnetic fields (Lee et al., 1990; 1991; 1993), corroborated by the relatively few boreholes that penetrate the base of the Mesozoic strata in the region. In contrast, seismic surveys have been carried out in much of the west of the region, and together with deep boreholes and the regional potential field maps, these have provided detailed constraints on the structural interpretation of that area.

Although the existence in this region of three distinct basement terranes is known with confidence, the position and nature of the boundaries between them is considerably less certain. The position of the north-eastern edge of the Midlands microcraton, against the Caledonide fold belt, is parallel to a number of structural lineaments apparent in the regional gravity field, and to seemingly deep-seated structures such as the Lilley Bottom Structure, which have influenced aspects of Cretaceous sedimentation (Hopson et al., 1996; Mortimore et al., 2001) and the Thringstone Fault (see the Central England region companion report) and other elements of the Charnwood boundary fault system and its south-easterly continuation (Lee et al., 1990; Pharaoh et al., 1987a; 2011). It seems likely that this terrane boundary is a fault zone with multiple strands and a complex history, possibly including thrusts dating from the Caledonian Orogeny, but the lateral extent of the fault zone, and the displacement within it, are unknown.

The location of the northern margin of the Variscan fold belt, the Variscan front, is rather better known, if it is accepted that the reversed faults and associated folding at the northern margin of the Weald basin are controlled at depth by Variscan thrusts. The southern edges of the Oxfordshire and Berkshire coalfields are thought to have been truncated by thrusting and folding at the Variscan front. To the east of the Hog’s Back, in the London area, the northern extent of Variscan folding and thrusting is known with less confidence: it could possibly extend as far north as the Wimbledon–Greenwich fault zone.

The position and nature of structures within the basement terranes is also uncertain in some respects. The Cliffe Fault, and the associated graben, were recognised from a cluster of deep boreholes in south Essex and in north Kent, on the Isle of Grain (Owen, 1971). Depiction of the fault’s westwards continuation is based in part on interpretation of lineaments in the local gravity anomalies, and in part on the inference that it is associated with the east–west periclinal folds in the Chalk and Palaeogene deposits in that area (as shown by Ellison et al., 2004). There, the exact position of this fault, as mapped, is a matter of judgement and interpretation. Given the inferred relationship with mapped folds, perhaps it would have been logical to align it with the east–west Chalk outcrop between Woolwich and Little Thurrock, but as the existence of the fault as a single strand and its relationship with the folding in the Chalk are only inferred, that depiction might have imparted an apparent precision that is not warranted. It is assumed that the Cliffe Fault is truncated to the west by the Wimbledon–Greenwich fault zone but the relationship of these fault structures is largely a matter of speculation. Note that there is a discrepancy between Figure 2 of Ellison et al. (2004), which shows an inlier of Silurian strata just to the north of the Cliffe Marshes Borehole (which found Cretaceous strata resting on the Silurian) (Ellison et al., 2004; Owen, 1971), and Figure 3 of the same publication, which shows only Devonian strata at this level. This discrepancy is probably due to drafting errors: the interpretation shown in their Figure 2 is preferred here.

The existence of the fault zone inferred in the basement beneath the Wimbledon–Greenwich fault zone is uncertain, and its nature is essentially unknown: the number of faults, the amount and direction of their dip, the sense and amount of their displacement and their relationship with faults mapped at the surface are all matters of speculation. The mapped surface faults in this zone should be regarded as indications of the possibility of major displacement at depth.

As found in the Thame district, the outcrop patterns of faulted strata (as mapped at the surface) are likely to indicate only the most recent movements. Older strata may have been displaced by greater amounts, and perhaps in different senses, compared with those indicated by offsets of surface strata. In detail, the fault zones mapped in this area are each quite complex (Horton, et al., 1995). The geometrical relationship between the intersecting fault zones is not well known: in particular it is not known whether fault elements at the south-western end of the Street Hill Fault are aligned with the Wheatley fault zone, or are truncated by it.

Furthermore, as noted in the previous section on faulting, the NGS3D model includes significant vertical offsets of Palaeozoic strata (totalling more than 1100 m) that appear to correspond to the Merton and the Street Hill faults, while no such basement displacement is associated with the Wheatley fault zone. However, it is likely that alternative interpretations are possible. For example, the Merton and Street Hill faults might be surface expressions of a single fault zone at depth, with major displacement also occurring in the basement beneath the Wheatley fault zone. Alternatively, three or more faults might be present in the Palaeozoic basement in this area, corresponding to each of the major faults found at the surface (or with none of them), with a total displacement equivalent to that attributed to the two faults shown in the current NGS3D model.

As discussed in previous sections, what is known of the composition of the basement within the region largely depends on what can be inferred from a small number of boreholes, interpretation of geophysical information, and knowledge of contiguous, or analogous, terranes outside the region. Analogues for the Variscan fold belt can be found in parts of Devon and Cornwall, but these areas are more than 150 km away. The Caledonian fold belt can be assumed to resemble counterparts in Wales, Cumbria and southern Scotland. The Neoproterozoic basement of the Charnwood terrane is exposed only in rather small areas of Leicestershire and Warwickshire (in the adjacent Central England region). Each of the basement terranes can be expected to include some folded and metamorphosed elements but as direct observation of their component rock units is limited to a small number of deep boreholes, their structure is uncertain. The relatively sparse borehole information means that the degree of heterogeneity in the composition of the basement terranes is also little known.

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

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

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

6.2 GROUNDWATER SYSTEMS IN THE THAMES VALLEY REGION

There is some information related to groundwater in the depth range of interest, i.e. between 200 to 1000 m depth in the Thames Valley region. However, the majority of the information is related to the relatively shallow groundwater system that is currently exploited for groundwater resources, typically to depths of < 100 m. Since groundwater movement and chemical composition can vary significantly over short lateral and vertical distances, even in the depth range of interest, the level of uncertainty related to groundwater systems in the depth range of interest is high. It will be important to develop a detailed understanding of groundwater movement and chemistry and their implications for a safety case during any future siting process or site characterisation.

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The large-scale groundwater flow systems in the Thames Valley region are conceptualised as being controlled by the broad distribution of geological units and the regional geological structure; the hydrogeological characteristics of those units; topography and the distribution of recharge; and other hydraulic boundary conditions, such as the River Thames and the Thames estuary to the east of the region.

The GVS for the Thames Valley region (Table 3) divides rock units into three broad lithostratigraphical systems: a thick sequence of younger sedimentary cover rocks from Permian to Neogene in age; an older

Carboniferous sedimentary cover rocks; and a sequence of relatively low permeability Proterozoic, early Palaeozoic and Devonian basement rocks and igneous intrusions.

Only the younger sedimentary cover rocks crop out within the region and so receive direct recharge. The oldest rocks that crop out in the region are the Lias Group in the north-west of the region, so neither the Mercia Mudstone Group, Sherwood Sandstone Group nor the Permian rocks, the lowest of the younger sedimentary cover rocks, receive direct recharge within the region.

The Chalk Group, Upper Greensand Formation, Lower Greensand Group and Great and Inferior Oolite groups form regionally significant principal aquifers that are widely used for water supply across the region. The Portland Stone Formation is of limited extent and does not form a high-productivity aquifer in this area. At depths of greater than about 200 m in the region, older rock units have been proven or inferred, including formations that form principal aquifers in other regions — e.g. Sherwood Sandstone and Tournaisian–Visean limestones.

Groundwater flow in the main aquifers (Great and Inferior oolites, Lower Greensand, Upper Greensand and Chalk) is generally downdip towards the centre of the London basin syncline. Therefore in the Chilterns (Chalk) and Cotswolds (Oolites) groundwater movement is predominantly towards the south-east, and in the Chalk of the Berkshire and Marlborough downs and the North Downs, eastwards and northwards, respectively. Groundwater flow directions in the Lower Greensand are also south-eastwards or eastwards, towards London.

Water within the confined zone in the oolites becomes brackish within a few kilometres of outcrop, indicating low rates of groundwater movement. However, the drawdown and recovery of water levels in the confined Chalk under London is indicative of regional groundwater flow systems from both the north (Chilterns) and the south (North Downs). Similarly, around Slough, there may be a contribution to groundwater in the confined Lower Greensand from the outcrop to the north.

Along the margins of the region, that broadly corresponds with the River Thames catchment, water in the Great and Inferior oolites is likely to flow north-westwards, in the opposite direction to the surface water catchment, due to the groundwater divide being displaced south-eastwards away from the scarp slope towards the dip slope.

There is no known head data for the Sherwood Sandstone and Tournaisian–Visean limestone aquifers. The Sherwood Sandstone is connected with its outcrop area to the north and north-west, but to the west there is no connection with the outcrop area due to a combination of being overstepped by the Mercia Mudstone and to faulting. The Tournaisian–Visean limestones are also not connected to their outcrop area.

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

- a groundwater system in the exposed younger sedimentary cover sequence from the latest Triassic to the Neogene
- a groundwater system within the sedimentary cover rocks of Carboniferous to Triassic age that are not present at crop in the region
- a relatively low permeability system consisting of Proterozoic, early Palaeozoic and Devonian basement rocks and igneous intrusions

There are some features within the region that may lead to separation of or enhanced flow between the different groundwater systems, for example associated with faulting or variations in the stratigraphy across the region. There are a number of rock units in the depth range of interest between around 200 and 1000 m that are known or inferred to have relatively low permeability, and which could therefore restrict vertical and horizontal movement of groundwater. These are discontinuous across the region due to lateral and vertical lithological changes, and to faulting. Compared with other regions there are relatively few deep anthropogenic structures that may affect the regional groundwater flow. All these features are discussed after a description of each of the three groundwater systems.

6.3.1 Hydrogeology of the exposed younger sedimentary cover sequence

6.3.1.1 CHALK

The Chalk is a fine-grained, pure limestone. The maximum thickness in the region is about 200–250 m. The uppermost White Chalk Subgroup contains soft white and hard nodular chalks, marl seams and flint beds.

The underlying Grey Chalk Subgroup is more argillaceous than the White Chalk and comprises blocky grey chalk underlain by rhythmic alternations of marls and marly chalks. There is often a glauconitic sandy marl at the base of the succession.

The Chalk forms a microporous aquifer, with low intergranular permeability but secondary fracture permeability; the fractures may be solution enhanced. It crops out around the margins of the London basin in the Chilterns to the north, the Berkshire and Marlborough Downs to the west and to the south in the North Downs (although the last are mainly outside the Thames Valley region). These areas act as recharge zones, with natural discharge by slow upwards leakage through the overlying London Clay, into the River Thames where the Chalk is exposed locally on the river bed.

Fractures are often developed above marl bands, hard nodular chalk or flint beds; locally the aquifer can behave in a karstic manner where the fractures have been enlarged by dissolution. The area with the greatest density of karst solution features in the Chalk occurs in the Chilterns, where there is an average of 21–30 solution features/100 km^2 (Edmonds, 1983), although this is likely to be an underestimate as most dissolution pipes have no surface expression. Many karst features, notably stream sinks and sinkholes are developed along the Chalk–Palaeogene boundary, whilst sediment-filled dissolution pipes are common beneath the clay-with-flints. Karst features are found in both recharge and discharge areas.

Where the Upper Greensand is absent, a spring line is present at the junction with the Gault Formation (BGS, 1984). Elsewhere springs occur at the level of the Risborough Rock and Totternhoe Stone (junction of Zig Zag Chalk Formation and underlying less permeable West Melbury Marly Chalk Formation).

At outcrop, yields from boreholes depend on intersecting fractures in the saturated aquifer; these are generally best developed in valley locations compared with below interfluves and within about 50–60 m of the water table. In the confined part of the London basin, the highest permeability occurs along the Thames and Lea valleys (Water Resources Board, 1972), as well as along the continuations of valleys present in the unconfined aquifer such as the Wandle and Mole. Under London, the Chalk is in hydraulic continuity with the overlying basal sands aquifer that includes the Thanet Formation, and where the Lambeth Group is permeable (mainly under eastern London), this plus the overlying Harwich Formation.

The groundwater is of calcium bicarbonate type. A redox boundary occurs close to the unconfined/confined boundary where a loss of oxygen leads to denitrification, and an increase in iron and manganese. Ultimately the waters become of sodium chloride type in the deepest part of the aquifer (Shand et al., 2003; Edmunds and Brewerton, 1997). Radiocarbon dating of water under central London indicates an age of 20 000 years. (Sumbler 1996). Changes in porosity and pore water chemistry with depth at the Faircross Borehole have been inferred to be associated with change in dominant mode of historic diagenesis, from mechanical compaction above 155 m below ground level to chemical compaction below this depth (Bloomfield, 1997).

In the Lea valley, chloride and total dissolved solids remain low due to the large amount of rapid throughflow caused by heavy abstraction over a considerable period of time (BGS, 1984). Depressed water levels under London have allowed saline water to ingress from the River Thames, and chloride can exceed 1000 mg/l. Historic over-abstraction below London has caused water levels to fall by over 95 m at Trafalgar Square, and currently levels in parts of central London remain more than 35 m below OD (Environment Agency, 2015; Ellison et al., 2004). The over-abstraction means that water levels in the confined aquifer were locally drawn down below the London Clay into the Chalk, they are now gradually recovering and locally lie against all formations from the Chalk to the London Clay (Environment Agency, 2015). Where the water level has been drawn down into the Chalk, dewatering of the overlying basal sands aquifer has allowed air to enter and led to the local oxidation of pyrite and the accumulation of poor-quality water in these sands. As water levels rise again this poor quality water enters boreholes (Kinniburgh et al., 1994).

6.3.1.2 Upper Greensand

The Upper Greensand comprises interbedded sands and sandstones, commonly speckled with glauconite. Some sandstones include cherty concretions and locally towards the top of the succession, a sandstone largely comprising of siliceous sponge spicules in a secondary siliceous cement (‘Malmstone’) occurs. The base is markedly diachronous, with arenaceous sediments reaching the western part of the region first. It forms a good aquifer around the Vale of Pewsey (just outside the region to the west) (Institute of Geological Sciences and Thames Water, 1978), but it is also utilised as an aquifer in the region between Wantage and Princes Risborough.

Depending on the lithology of the basal Chalk, the West Melbury Marly Chalk Formation, the water in the Upper Greensand may or may not be in hydraulic continuity with that in the overlying Chalk aquifer, with springs occurring both within the formations as well as at their common boundary. In Berkshire they are usually in hydraulic continuity (Sumbler, 1996), and around Princes Risborough sources abstract from the combined aquifers (BGS, 1984). However, around Benson, in south Oxfordshire they have different heads and elsewhere the head in the Upper Greensand is up to 25 m lower than that in the Chalk (Institute of Geological Sciences and Thames Water, 1978) indicating poor hydraulic connection between the two formations.

6.3.1.3 GAULT FORMATION

The Gault Formation extends across the entire London platform within the region. It directly overlies the Lower Greensand Formation and underlies the Upper Greensand Formation, which is in many places in hydraulic continuity with the overlying Chalk Group. It comprises mainly mudstone with variable amounts of silt: there are generally more silt grade particles in the west of the region. Its basal beds are commonly silty and sandy with layers of phosphatic pebbles. The lower parts are generally pyritic while the upper part is more calcareous.

Overall, the mudstones of the Gault Formation have low permeability and restrict groundwater flow, acting as a confining or leaky layer above, and controlling recharge to and discharge from, the Lower Greensand aquifer (Forster et al., 1994). The near-surface hydrogeology of the Gault Formation is strongly controlled by its depositional history, diagenesis and degree of weathering: the depth of weathering varies but rarely extends to 10 m (Forster et al., 1994). Osborne (1925) states that although the Gault in the Marlborough area holds little groundwater, joint and bedding planes, shelly layers and sandy laminae allow ‘sluggish percolation’, which in some cases is enough to replenish small domestic supply wells overnight.

Alexander et al. (1987) presents evidence for downward vertical groundwater flow through the Gault, towards the underlying Corallian Group aquifer in the north-west of the Thames valley at Harwell (NGR SU 4680 8644). A model of groundwater flow at Harwell combined the Gault, Lower Greensand and Kimmeridge Clay Formation (at depths of around 100 to 200 m below ground level) into a single low hydraulic conductivity layer, (Brightman and Noy, 1984).

Pore water in the Gault Formation generally has relatively low salinity, but salinity increases with depth, possibly related to downward vertical flow (Forster et al., 1994). Stable isotope data indicate recent local meteoric recharge mixed with small proportions of saline groundwater, but vary according to sample depth (Forster et al., 1994). Forster et al. (1994) notes that oxidation of pyrite, perhaps enhanced by microbial breakdown, could lead to acidic pore waters, which would enhance leaching, although this effect is likely to be buffered by reaction of calcite in the upper Gault.

There is no information in the references reviewed on the hydrogeology of this unit in the depth interval of interest.

6.3.1.4 LOWER GREENSAND

The Lower Greensand Group is generally thin or absent across the region, but at Faringdon it thickens to infill a south-east trending erosional trough that cuts down through the Kimmeridge and Ampthill clay formations into the underlying Corallian Group. Around Leighton Buzzard, the Lower Greensand Group is dominated by the Woburn Sands Formation. This cuts out the Kimmeridge Clay and Ampthill Clay formations and rests directly on the sequence from the Oxford Clay down to the Inferior Oolite. The base of the Woburn Sands Formation is therefore unconformable, but the top passes up conformably into the Gault, so its thickness is highly variable. The Lower Greensand is generally absent across the London platform. To the south, at outcrop around the Weald, the Lower Greensand can be split into five different formations (Folkestone, Sandgate, Bargate, Hythe and Atherfield Clay), but at depth the distinction between the beds below the Folkestone Formation tend to disappear and the group generally thins becoming less significant as an aquifer, especially where it is overlain by Chalk (Allen et al., 1997).

Seasonal fluctuations in water level in the aquifer are low, generally less than 1 m, reflecting the predominantly intergranular flow (Monkhouse, 1974; Allen et al., 1997). Under Slough, where the Lower Greensand is present below over 260 m of overburden, moderate yields have been obtained. Water levels were initially overflowing, but abstraction caused them to drop by more than 25 m and abstraction rates had to be reduced to protect the aquifer (Sumbler, 1996). Moderate yields were also obtained from depths of up 400 m from the Lower Greensand in the Chatham area from pumping stations at Nashendon, Capstone and

Luton (Dines et al., 1954) and in the Windsor area the Lower Greensand provides water at Winkfield and Ottershaw, an area where Chalk boreholes were dry (Dewey and Bromehead, 1915).

At outcrop, water from the Woburn Sands Formation generally has a carbonate hardness around 250 mg/l (as $CaCO_3$) the values being related to the cover of chalk-rich till. Radiometric dating of a pumped sample from a 332-m-deep borehole into the Lower Greensand at Slough indicates that the majority of water comes from storage with a contribution from the northern outcrop feasible (Institute of Geological Sciences and Thames Water, 1978). A 457-m-deep borehole at Sompting (in the adjacent Wealden region) proved 49 m of Early Cretaceous sandstone from a depth of 404 m; 35 m of medium to coarse-grained, uncemented or poorly cemented sandstone underlain by 14 m of fine-grained, clayey, glauconitic sandstone. The sequence yielded 1000 m^3/day of water at 21°C. Test pumping gave an average permeability of $1.97x10^{-12}$ m^2 (Downing and Gray, 1986). The water was fresh with pH of 6.6 and total dissolved solids of 110 mg/l (Burley et al., 1984). Water from another 459-m-deep borehole at Boxalls Lane, Weybourne (486190 149300), pumped from the Folkestone Formation at a depth of 400 m had a total dissolved solids content of 268 mg/l. However, a drill stem test at a depth of 241 m in a 252-m-deep borehole in Lower Greensand at Cliffe, Kent (572400 176320) had a pH of 8.5, total dissolved solids content of 2030 mg/l, indicating low rates of groundwater movement in this trough.

6.3.1.5 WEALDEN GROUP

The Weald Clay Formation forms the upper part of the Wealden Group. In the region it is dominated by mudstones, with subordinate siltstones and fine-grained sandstones, some of them calcareous, with shelly limestones and clay ironstone. It directly overlies the lower half of the Wealden Group, which includes two thick, dominantly sandstone units — the Tunbridge Wells Sand Formation; and the older Ashdown Formation. These two sandstone units are separated by the Wadhurst Clay Formation. Where they occur at outcrop and depths of < 200 m, these two sandstone units form secondary aquifers and are used for supply in the adjacent Wealden region.

The Weald Clay Formation is overlain conformably by the Lower Greensand aquifer. Little is known of the hydrogeology of the Weald Clay Formation in this region, or of the influence of the Weald Clay Formation on the hydrogeology of adjacent units, including locally and regionally important aquifers such as the Lower Greensand Group, the Tunbridge Wells Sand and the Ashdown formations. In the neighbouring Wealden region there is some evidence of groundwater flow along faults through the Wealden Group, including its mudstone-dominated units.

6.3.1.6 PORTLAND STONE FORMATION

The Portland Group unconformably overlies the Kimmeridge Clay Formation with a basal bed of lydite pebbles in a mottled clay or silty sand matrix (BGS, 1984). The upper part, the Portland Stone Formation, varies in lithology laterally, but generally comprises a lower sandy limestone, overlain by an arenaceous unit and an upper fine-grained limestone. It is underlain by the Portland Sand Formation or Glauconitic Beds (comprising micritic limestone around Swindon and calcareous sands and sandstones in the Oxford–Aylesbury area). The rocks often outcrop on higher ground where they are locally overlain by the Purbeck Group (limestone interbedded with marls, clays and sandy clays), which is in turn overstepped by the Whitchurch Sand Formation; they are locally underlain by silts and sands at the top of the Kimmeridge Clay Formation. The whole of the succession, from the Whitchurch Sand Formation down to the base of the sands at the top of the Kimmeridge Clay Formation (if present), is potentially in hydraulic continuity, with a spring line commonly developed at the base of the Portland Sand Formation.

There is no hydrogeological information for the Portland Stone Formation in this area in the references that have been reviewed.

6.3.1.7 ANCHOLME GROUP

The Ancholme Group in the region has a very varied lithology. It includes four mudstone-dominated formations: the Kimmeridge Clay Formation; the Ampthill Clay Formation; the West Walton Formation, and the combined Oxford Clay and Kellaways formations, and other intervening units that are locally used for water supply such as the Corallian Group and the Kellaways Sand Member. The Corallian Group lies within the lower part of the Ancholme Group. It is dominated by limestone and calcareous sandstone, with a relatively low proportion of mudstone. It lies between the Kimmeridge Clay and the Oxford Clay formations, and intercalates with mudstones of the West Walton Formation. Also within the lowest part of the Ancholme

Group, the Kellaways Sand Member, which forms the upper part of the Kellaways Formation, is a relatively permeable unit. The interbedding of more permeable formations within the mudstone-dominated units in the Ancholme Group is likely to have a major impact on the overall hydraulic properties of the group.

There is very limited hydraulic property information for any of the mudstone-dominated units in the Ancholme Group. Studies in the north-west of the Thames valley at Harwell have presented evidence for vertical groundwater flow through low permeability formations that include the Kimmeridge Clay and Oxford Clay formations, at depths of up to 300 m (Alexander et al., 1987). Alexander et al., (1987) states that it is not clear whether groundwater flow through mudstones is via fractures or intergranular, but that faults in mudrocks may be important in controlling flow rates in deep basins. As previously noted, a model of groundwater flow at Harwell combined the Gault, Lower Greensand and Kimmeridge Clay formations (at depths of around 100 to 200 m below ground level) into a single low hydraulic conductivity layer (Brightman and Noy, 1984).

The Kimmeridge Clay Formation comprises mainly mudstone, with kerogen-rich fissile mudstone beds (oil shales) at some depths, and some pyrite. There are subordinate beds of silty mudstone, siltstone and muddy limestone, and widespread cementstone nodule beds. In the top part of the formation are widespread sandstone and siltstone beds. Alexander et al. (1987) presents evidence for groundwater flow into the Kimmeridge Clay Formation in the north-west of the region at Harwell from adjacent aquifers, with downward vertical flow through the Kimmeridge Clay Formation towards the underlying Corallian Group aquifer. Horton et al. (1995) states that some groundwater occurs in the sands near the top of the Kimmeridge Clay Formation in the Thame area.

Horton et al. (1995) states that although the Ampthill Clay forms an aquiclude between the Corallian and Portland Stone Formation aquifers, small amounts of groundwater have been obtained from shallow wells in the Clay in the Thame area, and small springs arise from cementstone units near the boundary between the Ampthill Clay and Kimmeridge Clay formations. Some of these springs yield iron-rich groundwater, including one at Dorton near Thame with an SO_4 concentration of >2600 mg/l and an Fe concentration of about 85 mg/l.

The West Walton Formation consists of alternating calcareous mudstone and silty mudstone with carbonate mudstone and siltstone nodules. In the Oxford area, there are thicker mudstones; sand beds increase further south of this. The West Walton Formation includes a subunit, the Elsworth Rock (Jones et al., 2000), that forms a minor aquifer where it is present at outcrop and shallow (< 100 m) depths. The Elsworth Rock was formerly locally used for domestic and farm supplies in the Biggleswade area, and a number of small springs discharge from the formation along its outcrop (Moorlock et al., 2003). The Elsworth Rock is likely to affect the hydraulic properties of the West Walton Formation as a whole, increasing local permeability (Jones et al., 2000).

The upper third of the Oxford Clay Formation is blocky calcareous mudstone with thin beds of carbonaceous mudstone and calcareous siltstone. The middle part is predominately variously silty calcareous mudstone with beds of calcareous siltstone up to 0.3 m thick. The lowest third comprises fissile, organic rich shelly mudstone with subordinate beds of blocky mudstone and bands of cemented calcareous mudstone. One of a number of deep research boreholes in the north-west of the region at Harwell penetrated the Oxford Clay and a clay facies of the Corallian at depths of between around 260 and 360 m below ground level. The only depth interval in the Oxford Clay subject to field hydraulic testing was from 281.47 to 296 m below ground level, which gave a preferred hydraulic conductivity of 1×10^{-12} m/s and a specific storage of 2×10^{-7} (Alexander and Holmes, 1983). Groundwater pressure evidence from the Harwell research boreholes indicates upward vertical groundwater movement through the Oxford Clay Formation, from the underlying Great Oolite Formation aquifer towards the overlying Corallian Group aquifer. Assuming constant hydraulic properties and conditions throughout the formation, this gave an estimated groundwater flow velocity of 3×10^{-12} m/s (Alexander and Holmes, 1983). In the Bedford district, the Oxford Clay contains small quantities of poor-quality groundwater with high dissolved solids and iron contents (Barron et al., 2010). In the Marlborough area, groundwater discharging from the Oxford Clay was reported as often highly ferruginous (Osborne, 1925).

The Kellaways Formation directly overlies the Great Oolite and Inferior Oolite aquifers. At outcrop, the upper part of the Kellaways Formation is the Kellaways Sand Member, which directly underlies the Oxford Clay Formation, and is dominated by sands and calcareous sandstones. It forms a minor aquifer in the region where it is present at or close to outcrop, e.g. in the Bedford area (Barron et al., 2010) and the Thame area (Horton et al.,1995), with low permeability but observable groundwater flows (Jones et al., 2000). Horton et al. (1995) states that groundwater quality is generally poor, with saline groundwater recorded in a borehole near Oddington. Its presence is likely to affect the hydraulic properties of the Kellaways Formation as a whole, with increased porosity and permeability within this upper Kellaways Sand Member (Jones et al., 2000).

The Corallian Group, a local aquifer, comprises a complex association of calcareous sandstones and limestones with some silts and mudstones. The limestones tend to be rather soft, not well cemented and very porous (Jones et al., 2000). The Corallian Group is underlain by the Oxford Clay Formation and overlain by the Ampthill Clay Formation. Horton et al. (1995) states that the highest recorded yield from a borehole in the Corallian in the Thame area was 16.5 l/s for a drawdown of only 2 m, near Cowley, but that yields of 0.3 to 1.0 l/s are more typical, and less than this in outcrop areas where the saturated aquifer thickness is small. Water quality deteriorates where the aquifer is confined by overlying clays (Horton et al., 1995).

6.3.1.8 GREAT OOLITE AND INFERIOR OOLITE GROUPS

These strata crop out along the north-western margin of the region. The uppermost part of the Great Oolite Group, the Cornbrash Formation (3–5 m of fine-grained, shell-fragmental limestone with thin clays and marls), is ubiquitous, but below this the succession varies across the outcrop area becoming clay-dominated to the north-east. The Great and Inferior Oolite groups die out and are absent against the London platform, in the east, north-east and south-east of this region.

These oolitic limestones form an important aquifer in the Cotswolds, although due to being deeply dissected by rivers, they are predominantly unsaturated at outcrop and only form usable aquifers downdip as they become confined (Allen, 1997). Springs occur at the base of the Cornbrash, White Limestone and Taynton Limestone formations, and are very common along the scarp slope at the base of the Inferior Oolite Group. Where present, the Chipping Norton Limestone, although stratigraphically part of the Great Oolite Group, is in hydraulic contact with, and forms part of, the Inferior Oolite aquifer. The Northampton Sand Formation is generally only a good aquifer where weathering and oxidation has enhanced porosity within about 10 m of the ground surface (Barron et al., 2006)

The thin marl seams present within the limestones are unlikely to have an effect on regional flow, due to the prevalence of fractures; although on the local scale the direction of groundwater flow within a large fracture has been observed to change direction over time. Faults with throws of 30–50 m mean that locally the two aquifers are hydraulically connected; however the presence of faults may reduce permeability, seen by the lack of interference between boreholes during pumping tests (Allen, 1997). The Inferior Oolite is more fractured than the Great Oolite, possibly as it has a lower clay content (Allen et al., 1997).

The quality of water in both aquifers is similar at, or near, outcrop, hard and of calcium bicarbonate type. Downdip the water becomes more mineralised due to longer residence times in the aquifer. High specific electrical conductance values, associated with high sodium and chloride concentrations, in the deeply confined aquifer (Burley et al., 1984) suggest the influence of old formation water (Neumann et al., 2003).

6.3.1.9 LIAS GROUP

The Lias Group directly underlies the Great Oolite and Inferior Oolite groups. Below the Lias Group is the Mercia Mudstone Group. The Lias Group is has a very varied lithology including: the Whitby Mudstone Formation consisting of silty mudstone with thin limestone and conglomerate beds and reworked limestone concretions; the Dyrham and overlying Marlstone Rock formations comprising mainly mudstone and fine-grained sandstone with ironstone nodules and ferruginous; the Charmouth Mudstone Formation, a calcareous silty mudstone; and, at the base, the Blue Lias Formation, an interbedded limestone-mudstone sequence. The frequency of limestone beds in the Blue Lias Formation decreases towards the north and west. Some parts of the Lias Group form minor aquifers in the region, including the Dyrham, Marlstone Rock, and Blue Lias formations (Jones et al., 2000).

Hobbs et al. (2012) states that, as with many clay-rich formations, horizontal permeability in the Lias Group may be expected to be greater than vertical permeability by a factor of about two. Horton et al. (1987) states that springs emerge from the base of the Marlstone Rock Formation at outcrop in the Chipping Norton area, at the contact with underlying Lower Lias mudstones, with individual spring abstractions rarely exceeding 6819 m^3/year. In some parts of the Chipping Norton area, recharge to the Marlstone Rock Formation is believed to occur through the overlying Mid Jurassic limestones via major faults, and then to flow through the Marlstone Rock under confined conditions (Horton et al., 1987). Boreholes in the Marlstone Rock at Brackley, where the rest water level is more than 50 m below ground surface, have yielded up to 15 l/s, causing interference with other wells in area during test pumping. Elsewhere this aquifer has poor yields (Sumbler, 2002). Groundwater abstracted from the Marlstone Rock in this area is potable (Horton et al., 1987). The Blue Lias Formation at the base of the Lias Group typically consists of thin well-jointed limestones with intervening mudstones, which form a multilayered minor aquifer. Groundwater quality in the Blue Lias Formation where it is exploited as an aquifer is generally hard and often poor, sometimes saline or containing hydrogen sulphide (Jones et al., 2000).

6.3.2 Hydrogeology of the older, Carboniferous to Triassic, sedimentary cover sequence

6.3.2.1 MERCIA MUDSTONE GROUP

The Mercia Mudstone Group directly underlies the Lias Group across much of the region, but in areas where the Lias Group is absent, the Mercia Mudstone Group directly underlies the Inferior Oolite/Great Oolite groups. Across part of the region, the Tarporley Siltstone Formation of the Mercia Mudstone Group directly overlies the Sherwood Sandstone Group whereas in other parts, the group directly overlies older rocks, including Tournaisian–Visean, Early Devonian, and/or Silurian rocks.

The Mercia Mudstone Group almost entirely comprises mudstone and siltstone, including beds of laminated silty mudstone. Anhydrite and gypsum layers and nodules at many horizons, especially in upper half of the group. Thin beds of quartzose sandstone increase in number in the basal 10 m or thereabouts.

Overall, the Mercia Mudstone Formation is considered to be a non-aquifer, but where it is present at outcrop and shallow (< 200 m) depths, limited quantities of groundwater can sometimes be obtained from the formation where thin, fractured sandstone and siltstone layers or laterally impersistent lenses occur (Jones et al., 2000). The degree of fracturing is thought to be the main control on groundwater flow in these layers (Jones et al., 2000). However, the small outcrop area of such horizons means recharge to them is limited, and their generally thin nature and often lateral impersistence mean groundwater storage is relatively small (Jones et al., 2000). The other key control on the hydraulic properties of the Mercia Mudstone Group at shallow depths (generally < 30 m) is the degree and nature of weathering (Hobbs et al., 2002).

6.3.2.2 SHERWOOD SANDSTONE GROUP

The Sherwood Sandstone Group comprises fluviatile sandstones with subordinate mudstone beds, and includes nodules of anhydrite and gypsum within the mudstone beds (Sumbler, 1996). It generally rests on Warwickshire Group, apart from north-west where it overlies Devonian rocks. The overlying Mercia Mudstone Group is slightly more extensive and acts as a low permeability cap to this aquifer.

No information is available on the regional hydrogeological characteristics of this unit in the depth interval of interest in the region in the references reviewed.

6.3.2.3 UNDIVIDED PERMIAN ROCKS

A unit of Permian mudstones up to 400 m thick is thought to be present the Chippenham and Marlborough area. It is not shown on Table 3 as little is known about this rock unit and no aquifer properties data are known to be available.

6.3.2.4 WARWICKSHIRE GROUP

The Warwickshire Group is dominantly mudstone and siltstone with sandstones generally 1 to 30 m thick, thin seatearths and thin coals. The lower half of the group is dominated by sandstones. Sumbler (2002) describes the Warwickshire Group on the western margin of the Buckingham district as comprising 200 m of predominantly grey sandstone (Arenaceous Coal Formation). The Warwickshire Group was previously known as the Barren Measures Group (Jones et al., 2000). There is no information on the hydrogeological characteristics of this unit in the depth interval of interest, in the region in the references reviewed. However, it occurs at outcrop in central England, where it is used as an aquifer. In the group in that area, permeability is very variable reflecting the degree and type of cementation, and generally decreases with depth, due to the weight of overburden, compaction and increased cementation (Jones et al., 2000).

6.3.2.5 TOURNAISIAN–VISEAN LIMESTONES

The early Carboniferous (Tournaisian–Visean) limestones, sandstones and argillaceous rocks, where present, are underlain by Devonian rocks. In the south-central part of the region, they are overlain by Coal Measures (the Oxfordshire/Berkshire coalfield) and overstepped by Mercia Mudstone and Lias Group strata. These limestones, similar to those present in South Wales and the Mendips, comprise argillaceous, shelly limestones and silty mudstone.

The Tournaisian–Visean limestones are unconnected to any outcrop and recharge area. There is no information on karst development in the limestones in this area and no information on their hydrogeological characteristics in the depth interval of interest in the references reviewed.

6.3.3 Hydrogeology of the basement rocks and igneous intrusions

There is no information on the hydrogeological characteristics in the depth interval of interest in the references reviewed for any of the basement rock units or igneous intrusions present in the region, although by analogy with similar units in other regions, relatively low permeability compared with the overlying sedimentary cover sequences is expected.

6.4 EVIDENCE FOR CONNECTION AND SEPERATION BETWEEN GROUNDWATER SYSTEMS

6.4.1 Separation of aquifers

The Chalk and Upper Greensand aquifer is always separated from the Lower Greensand aquifer by some thickness of the Gault Formation. However, below the Gault, aquifers locally abut each other due to erosion and overstepping, so the Lower Greensand is locally above and hydraulically connected to the underlying Portland Stone Formation and elsewhere the Great and Inferior Oolite groups. The Mercia Mudstone is more extensive than the Sherwood Sandstone and hence there is always some thickness of this mudstone overlying the sandstone and separating it from younger permeable strata. Locally the Tournaisian–Visean limestones are overlain by the Great and Inferior Oolite groups, with potential for hydraulic connection.

6.4.2 Connection of aquifers

6.4.2.1 GEOLOGICAL PATHWAYS

In some parts of the region, faulting has caused juxtaposition of potential rock types of interest (PRTI) against principal aquifers and other local aquifers. For example, in the south-west of the region a series of faults have juxtaposed PRTIs against aquifers at depths of between around 400 to 1000 m. These faults have juxtaposed the Kimmeridge Clay Formation against the Portland and Corallian groups, and the Kellaways and Oxford Clay formations against the Corallian, Great Oolite and Inferior Oolite groups. Also in the far west of the region, faulting below 200 m partially juxtaposes the Kellaways and Oxford Clay formations and the Lias Group against the Great Oolite Group. Such faults could create pathways for groundwater flow between PRTIs and more permeable rock units, or produce isolated blocks within aquifers bounded by faults across which groundwater flow is minimal, e.g. when fault gouge infills the fault plane (Jones et al., 2000). However, there is no evidence that either of these occurs in the region.

Groundwater level evidence from the Harwell research boreholes indicates upward vertical groundwater movement through the Oxford Clay Formation, from the underlying Great Oolite Group aquifer towards the overlying Corallian Group aquifer with an estimated groundwater flow velocity of 3×10^{-12} m/s (Alexander and Holmes, 1983). However, the presence of large numbers of springs wherever permeable strata are underlain by less permeable ones throughout the area indicates that there is likely to be limited, if any, hydraulic continuity between the main aquifer units.

There are no known thermal springs in the region.

6.4.2.2 ANTHROPOGENIC PATHWAYS

There are few mineral, including hydrocarbon, or geothermal resources in the Thames Valley region (Chapter 8). No mineral deposits are known to have been worked deeper than 100 m, and there is no known potential for hydrocarbon, mineral or geothermal energy resource development in the immediate future. There are clusters of boreholes drilled to >200 m in the region, most of which are related to assessment of a coalfield in Oxfordshire and Berkshire or construction projects in central London and around the Thames estuary (Chapter 8), but no evidence that these have affected the regional groundwater regime. In the Chalk, extensive adit systems were constructed laterally from water supply boreholes from the mid-19th to early 20th centuries (Whitaker, 1921), however, these are all well above the depth range of interest.

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

This section is subdivided into three parts corresponding to glaciation, permafrost and seismicity. In each a national-scale context is provided, followed by a regional-scale evaluation for the Thames Valley 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 2016b; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next one million years is open to conjecture (Loutre and Berger, 2000). This is because the impacts of global warming and the current melting of the Greenland Ice Sheet on the long-term climate system are poorly understood, although the general scientific consensus is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions means that their occurrence cannot be discounted.

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

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

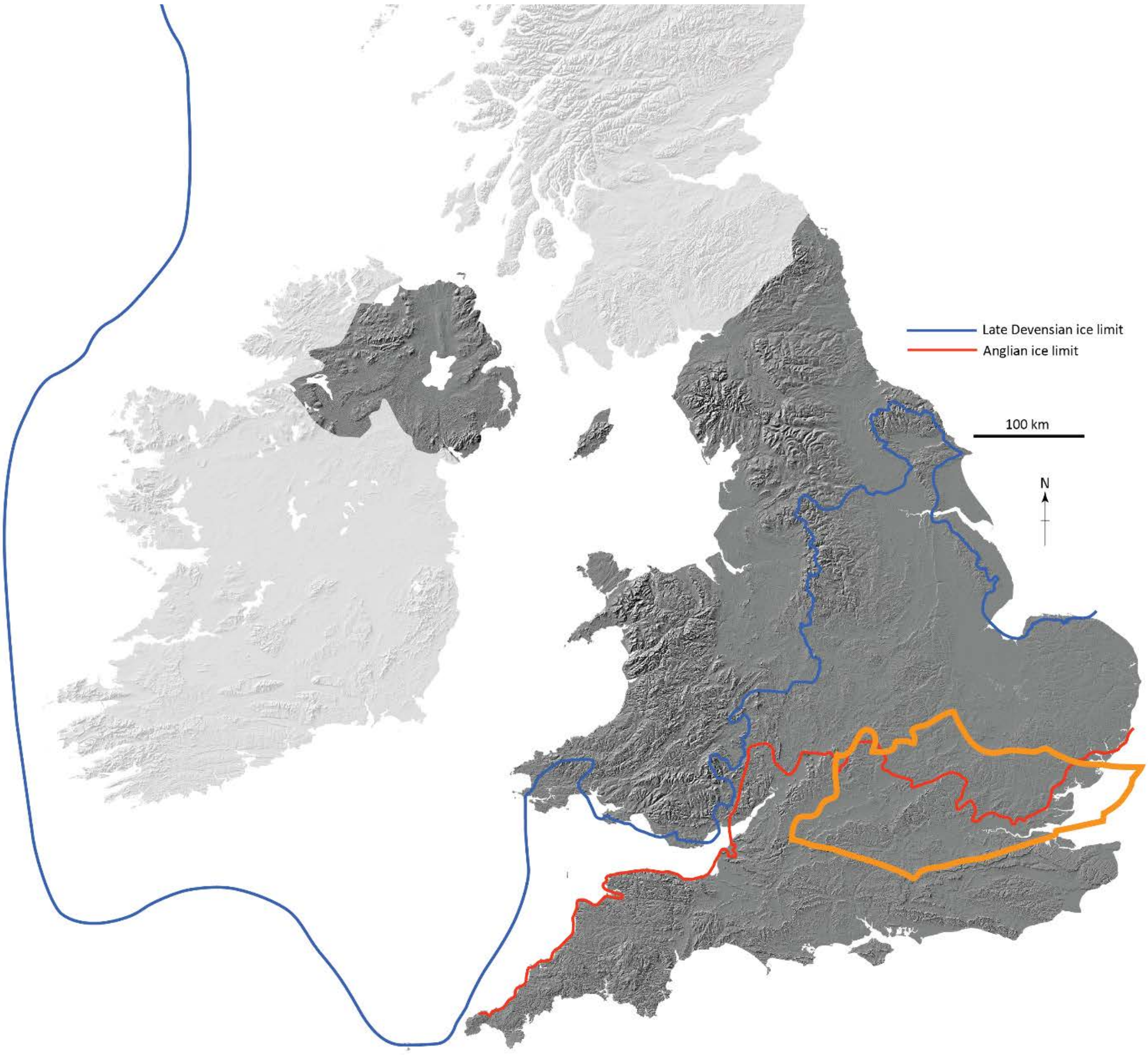


Figure 19 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (about 480 to 430 ka) and late Devensian (about 30 to16 ka). The location of the Thames Valley region is delineated by the orange line. Produced using Copernicus data and information funded by the European Union — EU-DEM layers. © EEA

7.2.2 A regional perspective

It is widely accepted that the Thames Valley region is situated beyond the limits of highland and lowland scale glaciation, but was affected by one continental scale glaciation (the Anglian Glaciation) during the last two and half million years (Quaternary Period; see Figure 19: Shaw et al., 2012; RWM 2016b). During this glaciation ice extended into the Thames valley as far south as north London, causing parts of the River Thames to be diverted. 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 (Loutre and Berger, 2000; RWM, 2016b). Important natural processes that may locally affect the uppermost depth range of interest include the incision of tunnel valleys by fast-flowing meltwater streams that occur beneath the glacier (RWM, 2016b). An example of a tunnel valley occurs beneath parts of the modern River Lea in east London and Hertfordshire, extending down in places to 60 m beneath ground level. Other tunnel valleys cut through the Chiltern Hills. The region may also be affected by isostatic rebound and/or a glacier forebulge relating to the glaciation of an adjacent onshore area (e.g. East Anglia, Central England and the North Sea: RWM, 2016b)). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (RWM, 2016b). The coastline of the Thames Valley region makes coastal areas, for example the Thames estuary, 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).

7.3 PERMAFROST

7.3.1 A UK-scale context

Permafrost (frozen ground) occurs when the temperature of the ground remains below 0°C for at least two consecutive years (French, 2007). Permafrost, therefore, develops where average air temperatures are much colder than the present day and consequently there is potential for significant thicknesses of permafrost to develop over decadal to centennial timescales (Busby et al., 2014). It is also important to note that permafrost and glaciation are not synonymous. Whilst many glaciated areas are subjected to periglacial processes, not all areas affected by permafrost will become glaciated. For example, areas situated to the south of the major limits of glaciation in the UK (see Figure 19) have all been affected by permafrost as indicated by the extensive weathering of surface geological materials (Shaw et al., 2012). Permafrost is important because its presence can affect the subsurface within the depth range of interest by altering groundwater behaviour and chemistry. This is especially the case if the current ground surface has been lowered by glacial erosion (Shaw et al., 2012).

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

7.3.2 A regional perspective

Under future cold climates over the next million years, it is likely that the Thames Valley region will be subjected to the development of permafrost to a depth of a few hundred metres (Shaw et al., 2012; French, 2007; Busby et al., 2014; RWM, 2016b). The development of permafrost can affect groundwater chemistry and behaviour (French, 2007; Busby et al., 2014).

7.4 SEISMICITY

7.4.1 A UK-scale context

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

Earthquake activity is greatest at the boundaries between the Earth's tectonic plates, where the differential movement of the plates results in repeated accumulation and release of strain (Figure 20). However, earthquakes can also occur within the plates far from the plate boundaries, and where strain rates are low. Such earthquakes are often referred to as intraplate earthquakes.

The UK lies on the north-west part of the Eurasian plate and at the north-east margin of the North Atlantic Ocean (Figure 20). The nearest plate boundary lies approximately 1500 km to the north-west where the formation of new oceanic crust at the Mid-Atlantic Ridge has resulted in a divergent plate boundary associated with significant earthquake activity. Around 2000 km south, the collision between Africa and Eurasia has resulted in a diffuse plate boundary with intense earthquake activity throughout Greece, Italy and, to a lesser extent, North Africa. This activity extends North through Italy and Greece and into the Alps. The deformation arising from the collision between the African and European plates results in compression that is generally directed 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 structure of the crust and have been the locus of later deformation. Earthquake activity in the UK is generally understood to result from the reactivation of these existing fault systems by present day deformation, although such faults need to be favourably orientated with respect to the present day deformation field in order to be reactivated (Baptie, 2010).

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

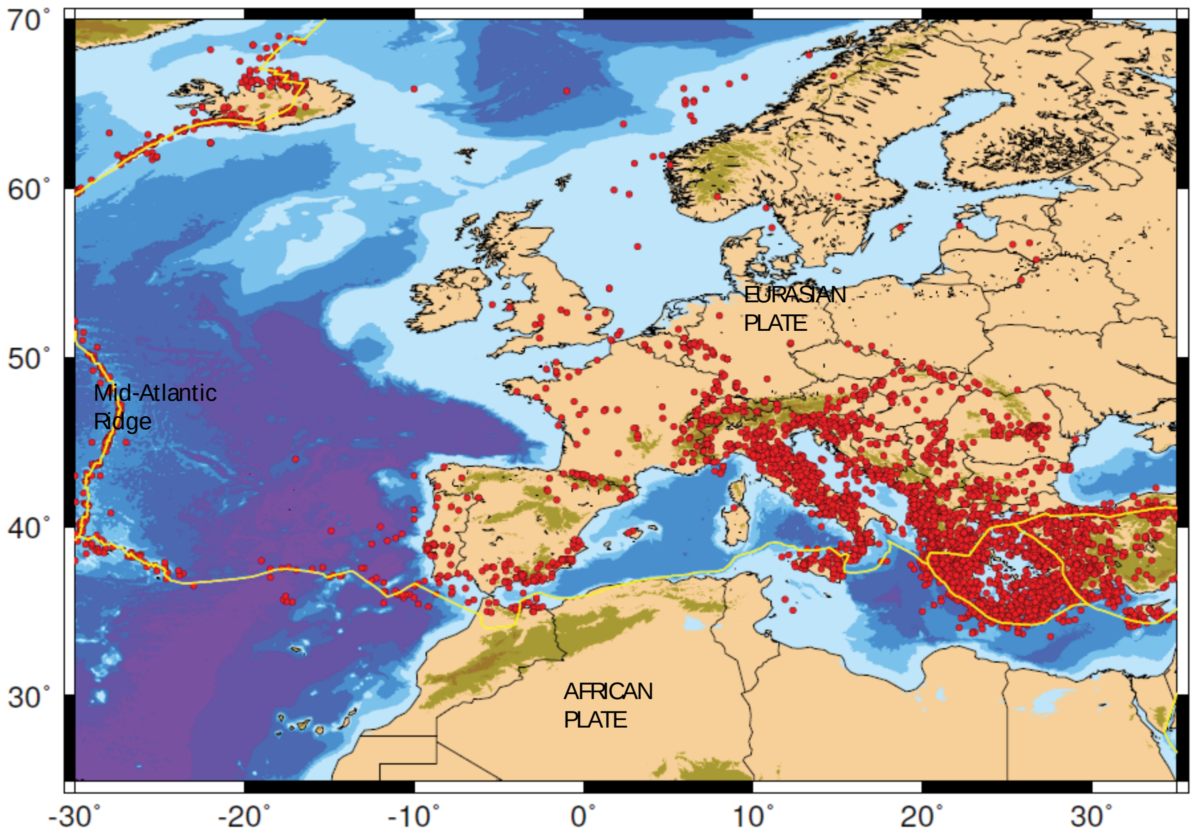


Figure 20 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

7.4.2 Seismicity catalogue

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

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

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

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

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

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

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

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

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

It is generally observed that the geographical distribution of British seismicity of the modern instrumental period follows rather closely the same distribution as the historical record of the last 300 years. However, there are three significant exceptions to this: south-west Wales, the Dover Straits, and Inverness. In these areas there was an intense historical seismic activity (as shown by the squares in Figure 21) that does not correspond to an intense instrumental seismicity. The Dover Straits area is notable for having produced relatively major (≥5 Mw) earthquakes in historical times (the last in 1580) and very little since.

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

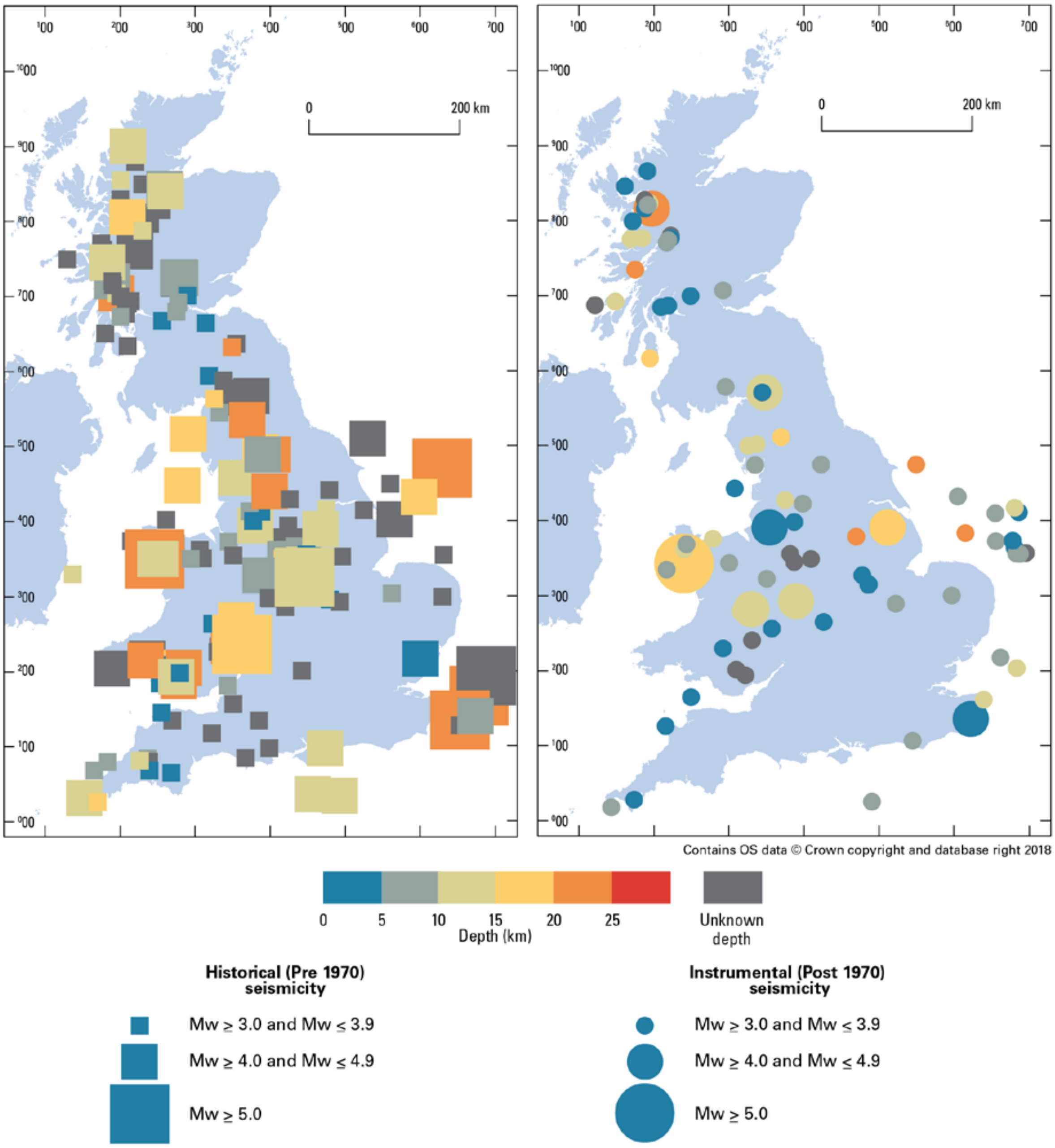


Figure 21 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological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

7.4.3 Earthquake depths

No earthquake in the UK recorded either historically or instrumentally is known to have produced a surface rupture. Typical fault dimensions for the largest recorded British earthquakes are of the order of 1–2 km. Therefore, it is difficult to accurately associate earthquakes with specific faults, particularly at depth, where the fault distributions and orientations are unclear and because of the uncertainties associated with depth estimates. The uncertainties in the focal depths determined for earthquakes are generally large, up to a standard deviation of ±10 km. Figure 22 shows the distribution of focal depths in the catalogue. These are distributed throughout the crust and the maximum depth in the catalogue is 28 km. This suggests that there is a relatively broad seismogenic zone, i.e. the range of depths in the lithosphere where earthquakes are generated. The larger earthquakes (e.g. the 7 June 1931 Mw 5.9 Dogger Bank earthquake, the 19 July 1984 Mw 5.1 Lleyn earthquake) tend to occur at greater depths (Figure 22).

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

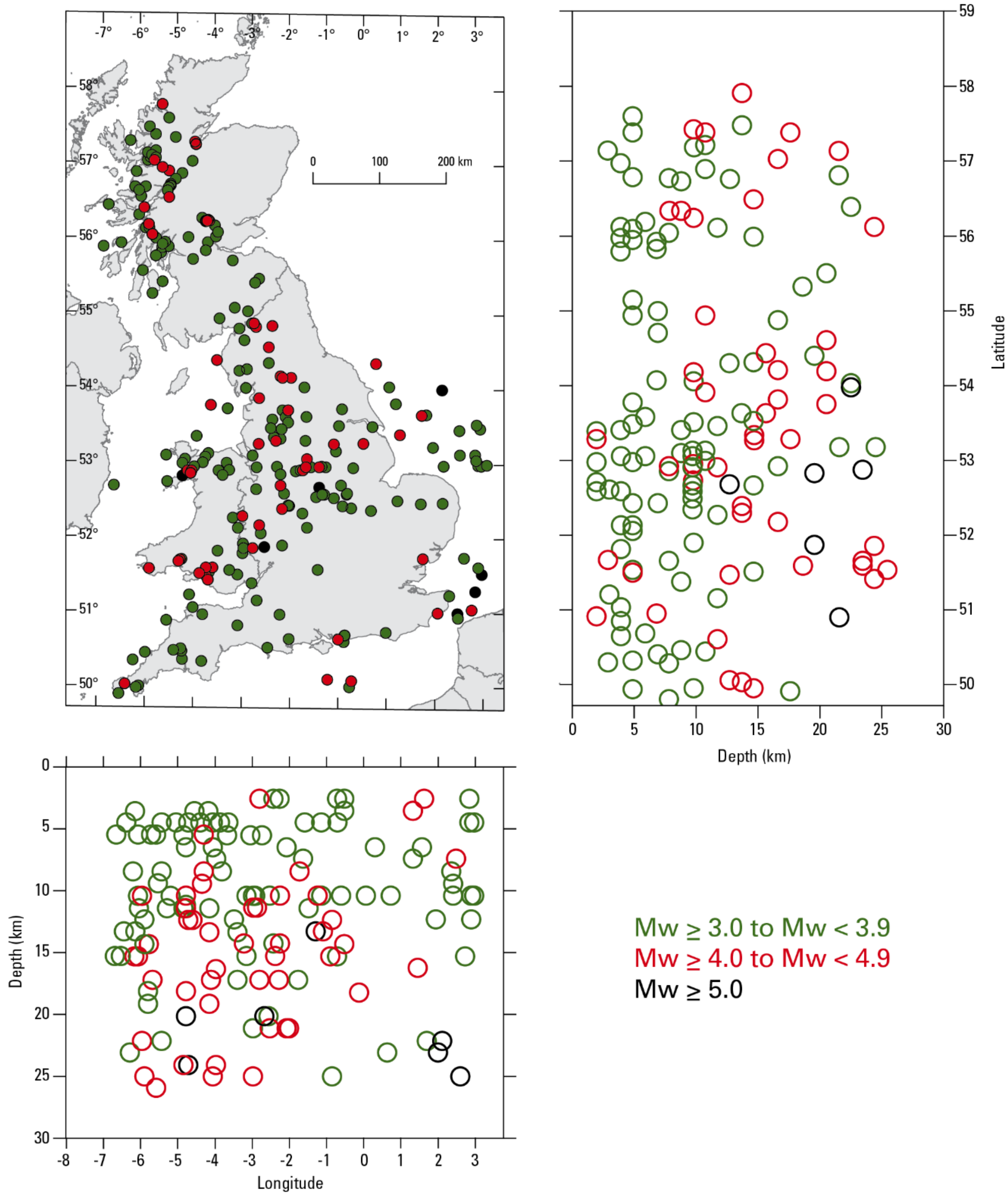


Figure 22 Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance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

7.4.4 Maximum magnitude

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

The maximum magnitude (Mmax) can be constrained by fault length, i.e. any large earthquake requires a sufficiently large structure to host it, and this certainly limits the locations where great earthquakes (M>8) can occur. In intraplate areas one cannot apply such criteria because there are many examples of strong (Mw 7) earthquakes occurring in virtually aseismic areas (e.g. Johnston et al., 1994). Furthermore, in any low-seismicity area, the length of the seismic cycle may be longer than the historical time window that captures the largest observed possible event (Musson and Sargeant, 2007). For these reasons, maximum magnitude is very much a matter of judgement in an area like the UK. Ambraseys and Jackson (1985) considers the largest possible earthquake in the UK to be smaller than Mw 6.0, considering the absence of any evidence for an earthquake above Mw 6.0 in the last 1000 years. For onshore seismicity the historical limit could be set even lower, around Mw 5.5 because historical onshore earthquakes have never been larger than Mw 5.1 (Musson, 2007; Musson and Sargeant, 2007). However, there is palaeoseismic evidence from Belgium for prehistoric earthquakes between 6.5 and 7.0 in magnitude (Camelbeeck and Megrahoui, 1996; Camelbeeck, 1999). Therefore, we cannot rule out the occurrence of an earthquake that may have a larger magnitude than the largest magnitude observed in the British seismicity catalogue and may have occurred before the beginning of the historical catalogue.

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

7.4.5 Earthquake activity rates

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

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

where N is the number of earthquakes per year greater than magnitude M. 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 1) and computes a 5x5 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 - 0.993 M. This is roughly, equivalent to an earthquake occurring somewhere in the British Isles with a magnitude of 5 Mw 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 6.0 Mw 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

The Thames Valley region has significantly fewer earthquakes than elsewhere in mainland Britain (Figure 23). There is only one observation of an earthquake with a magnitude of 4.0 Mw or greater. However, this is probably one of the most famous earthquakes to have occurred in the UK and was the most damaging earthquake since 1580 (Musson, 1994). This earthquake occurred on 22 April 1884 and the epicentre was near the village of Peldon in Essex, around 10 km south of Colchester and was thoroughly investigated by Meldola and White (1885). The earthquake had a relatively modest magnitude of 4.3 Mw and occurred where there is no other seismic activity is known to have occurred. However, it caused extensive damage to houses and churches near the epicentre (Meldola and White, 1885). The high levels of damage are a result of the shallow focus (< 5 km) and possibly local site effects.

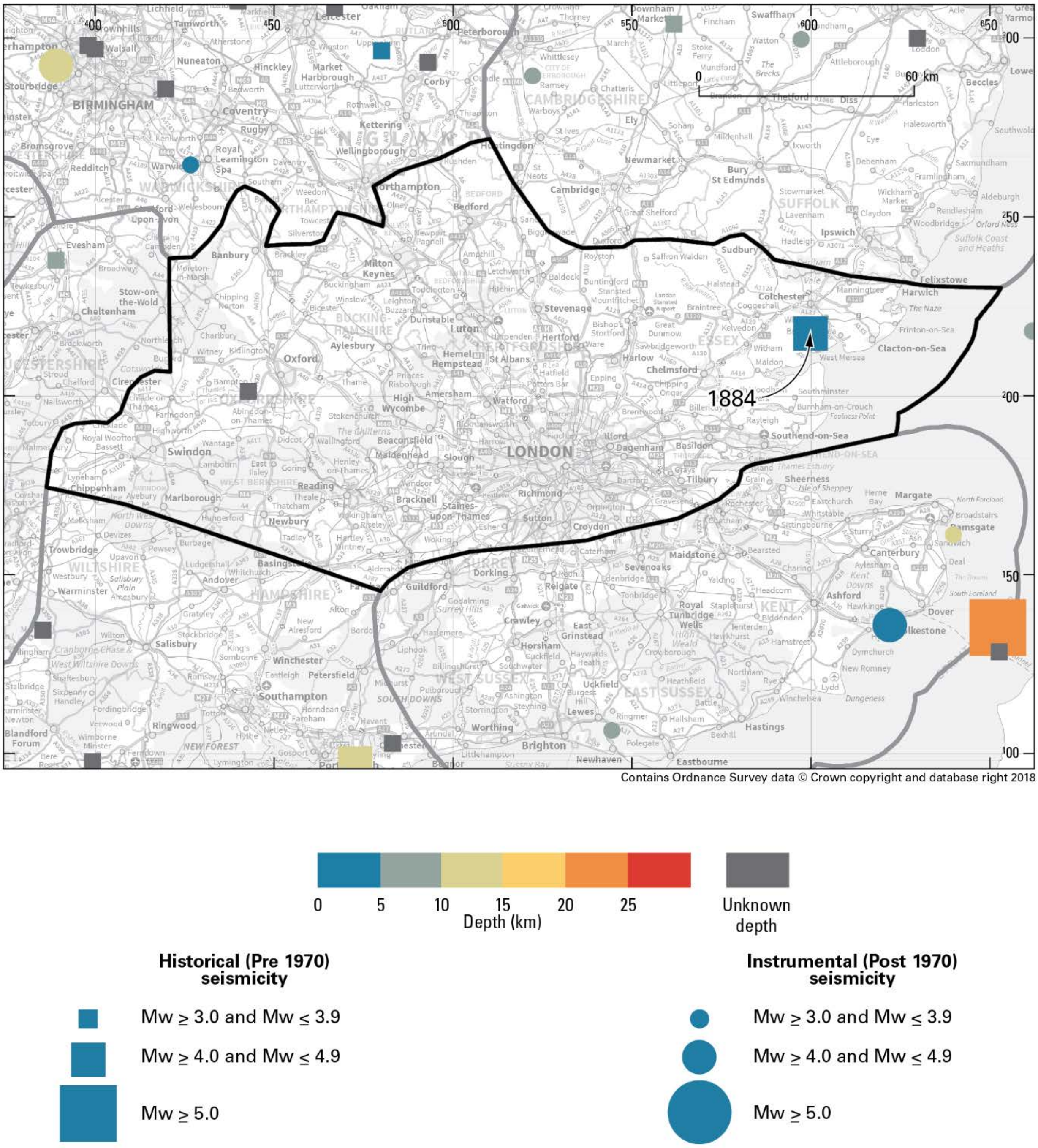


Figure 23 Historical and instrumentally recorded earthquakes in the Thames Valley region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data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

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

This section explains what is known of mineral resources in the Thames Valley 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 THE REGION

Figure 24 shows the distribution of mineral resources in the Thames Valley region. A large part of the west of the Thames Valley region is underlain by the Oxfordshire and Berkshire Coal Measure sequence which has never been mined. Shallow underground workings for commodities such as chalk, building stone and sand are scattered throughout the region.

8.3 COAL AND RELATED COMMODITIES

The Oxfordshire and Berkshire coalfield lies in the west of the region. This coalfield has been evaluated but has not been mined. The strata are mainly Upper Coal Measures and typically the coals are thin and of low quality. A total thickness of 7.85 m of coal was recorded in the Steeple Aston borehole, but the thickest succession was proved at Apley Barn, near Witney, where Coal Measures were intersected between 250 and 1210 m below NGS datum. Here the total combined thickness of coal is 8.8 m, with the thickest seams being 1.46 and 1.49 m. It is thought that these strata link at depth with the exposed Warwickshire coalfield to the north-west. The Oxfordshire and Berkshire coalfield is not considered economic, and it is unlikely that it will be mined in the foreseeable future.

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

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

No evaporite deposits occur in this 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.

Bedded iron ores occur in the Banbury and Northampton areas, annotated on Figure 24, which were mined on a modest scale in the 19th century. Neither workings nor resources exceed 100 m below NGS datum.

8.6 VEIN-TYPE AND RELATED ORE DEPOSITS

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

8.7 HYDROCARBONS (OIL AND GAS)

There are no hydrocarbon fields in the region. Gas was discovered near Twyford, south of Buckingham, but in sub-economic quantities and was not developed. There are no known resources for unconventional hydrocarbons.

8.8 GAS STORAGE

There are no planned, under construction or operating underground gas storage (UGS) facilities in the Thames Valley region. Whilst there were early assessments during the 1960s for town gas storage in porous rocks at various locations across the region, notably around Chipping Norton in the north-west, Brackley in more central parts and Cliffe in the east, there seems little immediate prospect for UGS in the region, including the offshore area being considered.

8.9 GEOTHERMAL ENERGY

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

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are clusters of deep (greater than 200 m below NGS datum) boreholes in the region (Figure 25). These are mainly related to the assessment of the Oxfordshire and Berkshire coalfield and construction projects around central London and the Thames estuary.

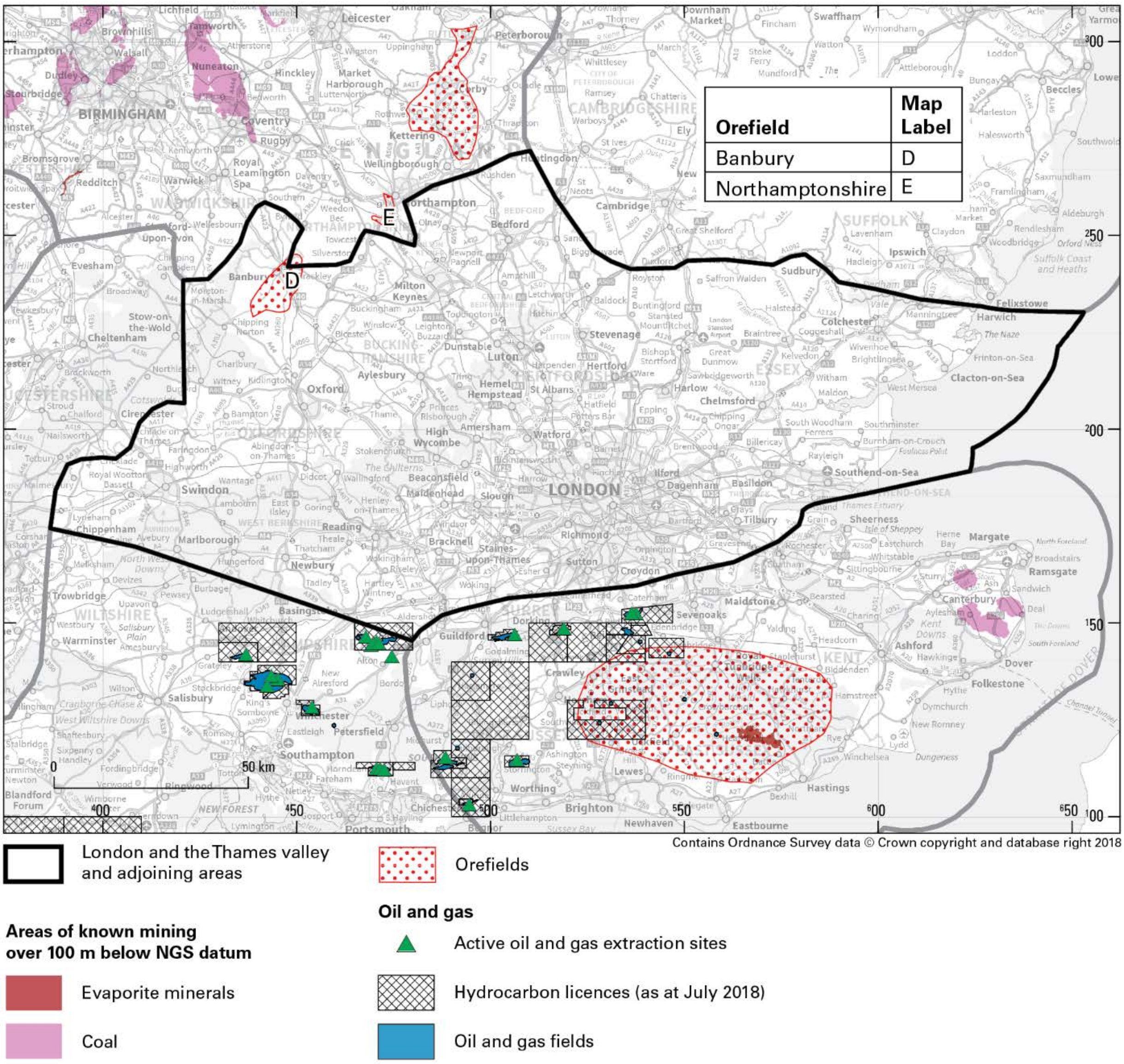


Figure 24 Distribution of mineral resources in the Thames Valley region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields and underground gas storage licence areas are not shown. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

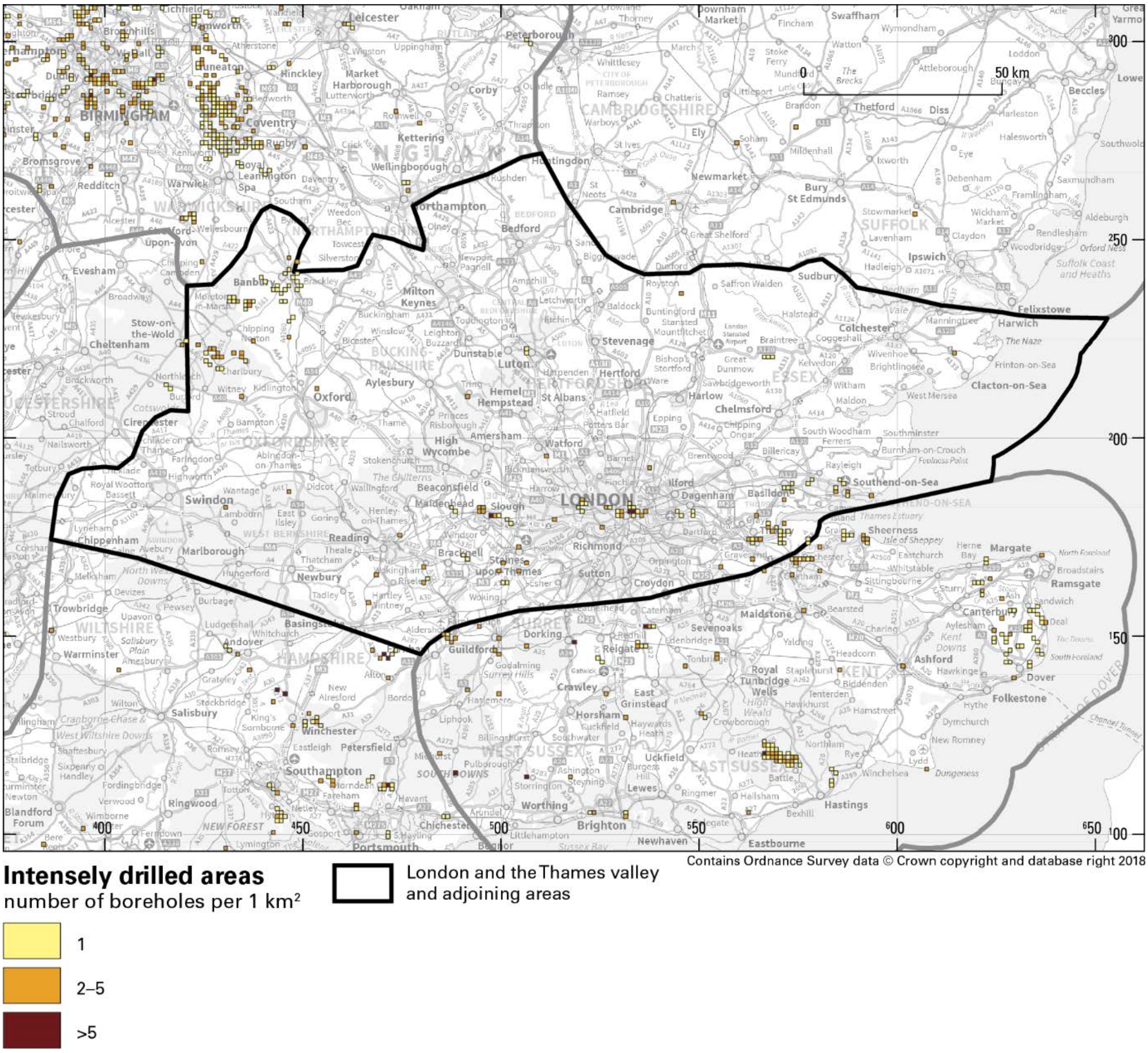


Figure 25 Location of intensely drilled areas in the Thames Valley region, showing the number of boreholes drilled per 1 km^2, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance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

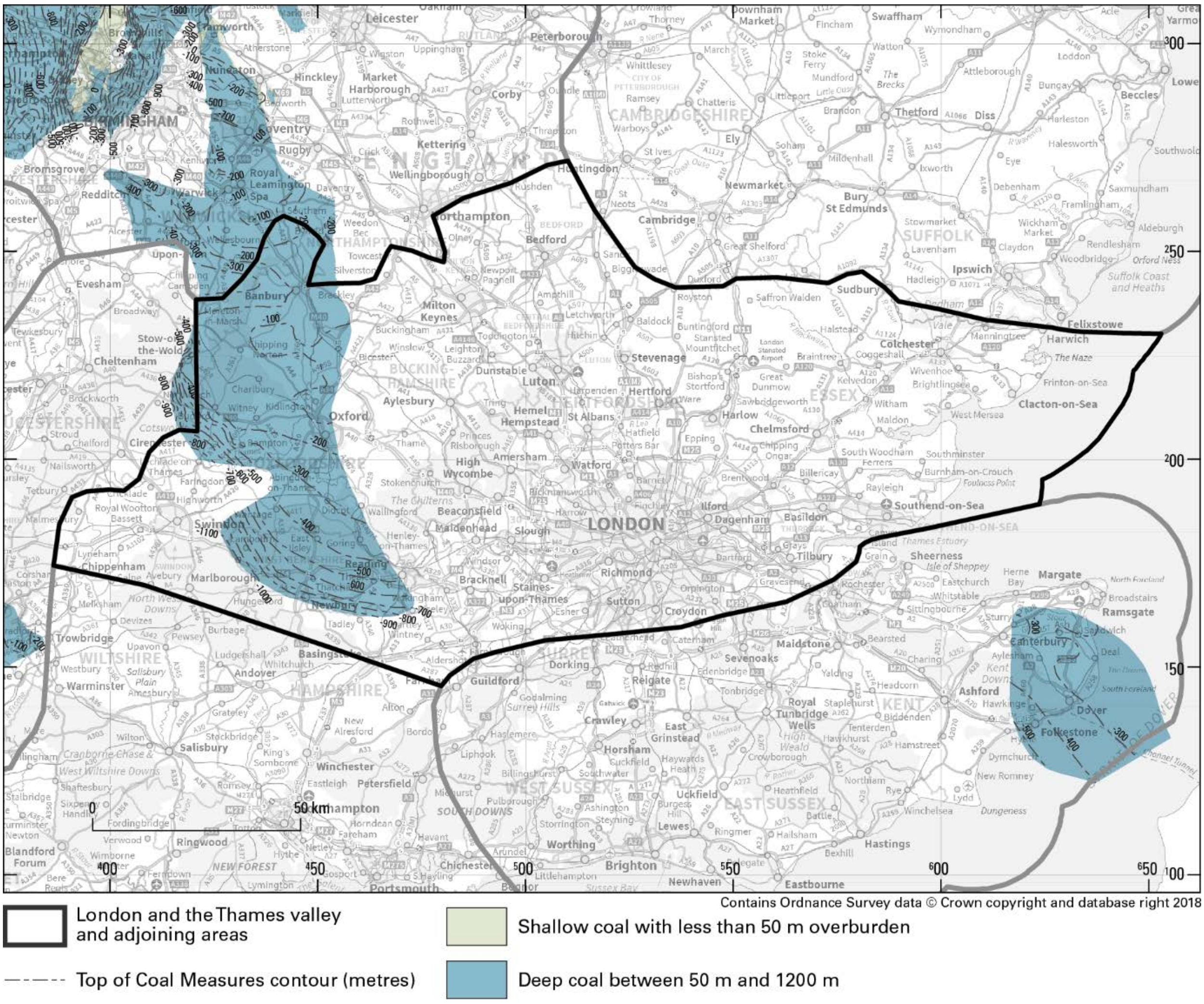


Figure 26 Distribution of coal resources in the Thames Valley region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

8.11 SUPPORTING INFORMATION

8.11.1 Hydrocarbons (oil and gas)

The hydrocarbon fields displayed on Figure 24 are provided by the hydrocarbon industry to the Oil and Gas Authority. They represent the extent of known hydrocarbon resources usually shown by the oil or gas contact with water within the hydrocarbon trap structure.

The hydrocarbon licence areas displayed on Figure 24 represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place.

8.11.2 Coal and related commodities

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

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

8.11.3 Borehole depths

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

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

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

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Borehole locations

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

Geothermal energy resources

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

DOWNING, R A and GRAY, D A. 1986. Geothermal energy: the potential in the United Kingdom. (London: HMSO for the British Geological Survey.) ISBN 0118843664.

Hydrocarbon resources

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