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National Geological Screening: the Wealden district

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Commissioned Report CR/17/099

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/099

National Geological Screening: the Wealden district

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

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Acronyms and abbreviations

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

Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1 Introduction

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

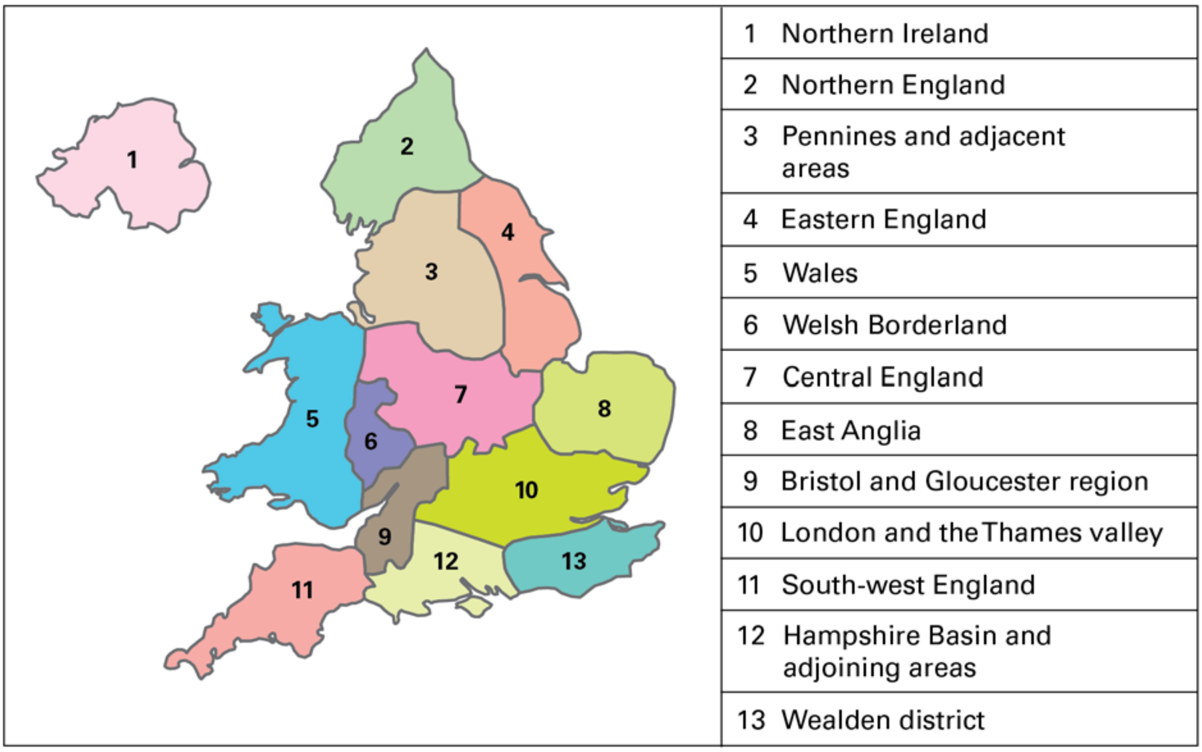


Figure 1 The BGS region boundaries as defined by the Regional Guides series of reports (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html). British Geological Survey © UKRI 2018.

2 Background

2.1 NATIONAL GEOLOGICAL SCREENING GUIDANCE

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

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

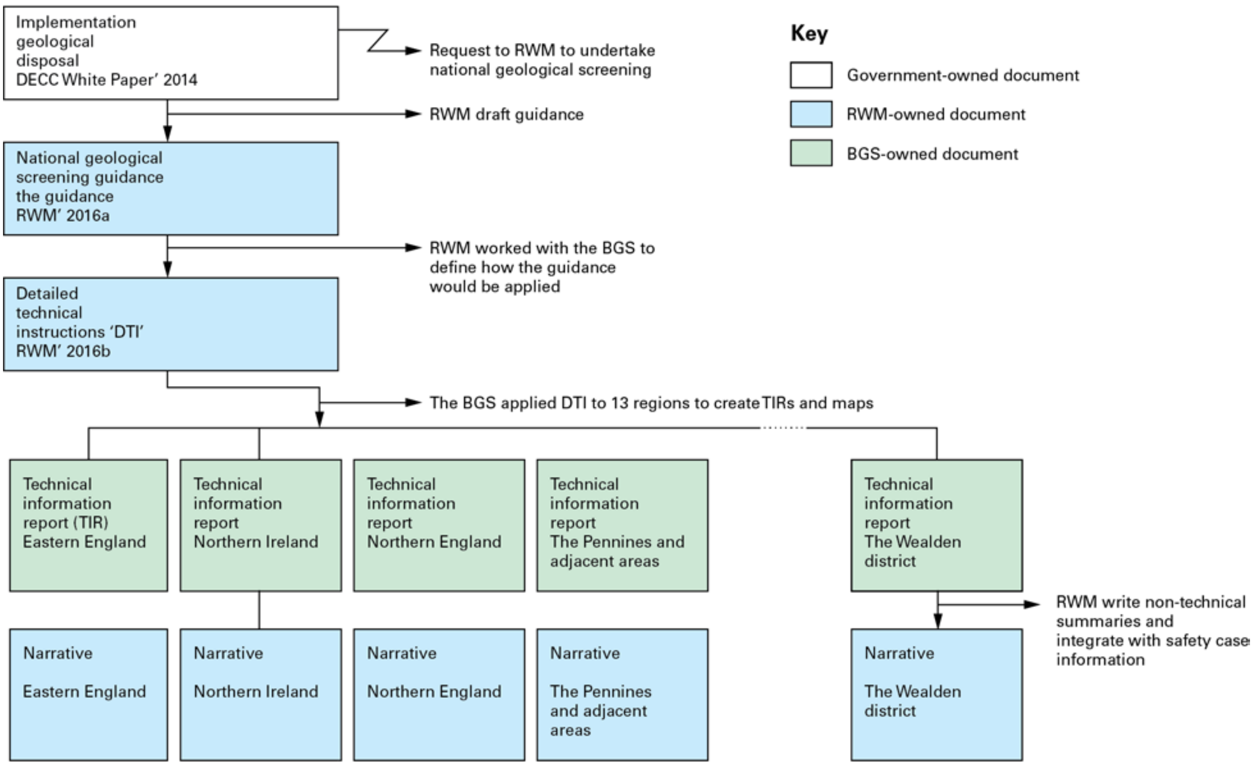


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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

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

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

2.2 DETAILED TECHNICAL INSTRUCTIONS

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

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

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

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

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

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

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

i. **Rock type**

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

ii. **Rock structure**

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

iii. **Groundwater**

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

iv. **Natural processes**

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

v. **Resources**

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

3 The Wealden region

Geographically, the Wealden region can be divided into three areas: the Weald, which forms the large central portion, the North Downs and the South Downs, both formed by the Chalk (Figure 3). The North Downs are a range of hills extending from mid Surrey eastwards through northern and eastern Kent. They are bounded to the south by a steep escarpment but fall away gently to the north, passing into low-lying areas of coastal north Kent and north Surrey. The South Downs form a range of hills similar to the North Downs, except that they are bounded by a steep slope facing to the north and slope away gently towards the south. They extend from south-east Hampshire eastwards through Sussex to Eastbourne. The Wealden region also includes small parts of the Hampshire Downs, which mostly lie outside the region to the west.

The Weald is a broad area of ridges separated by clay vales of various widths. It occupies the southern parts of Kent and Surrey, and the northern parts of Sussex, extending into the eastern fringe of Hampshire. The central portion, which is relatively hilly, is known as the High Weald. The surrounding Low Weald is mostly low-lying, with the Greensand Ridge, a series of subsidiary escarpments and narrow clay vales, occurring as the Chalk downlands are approached.

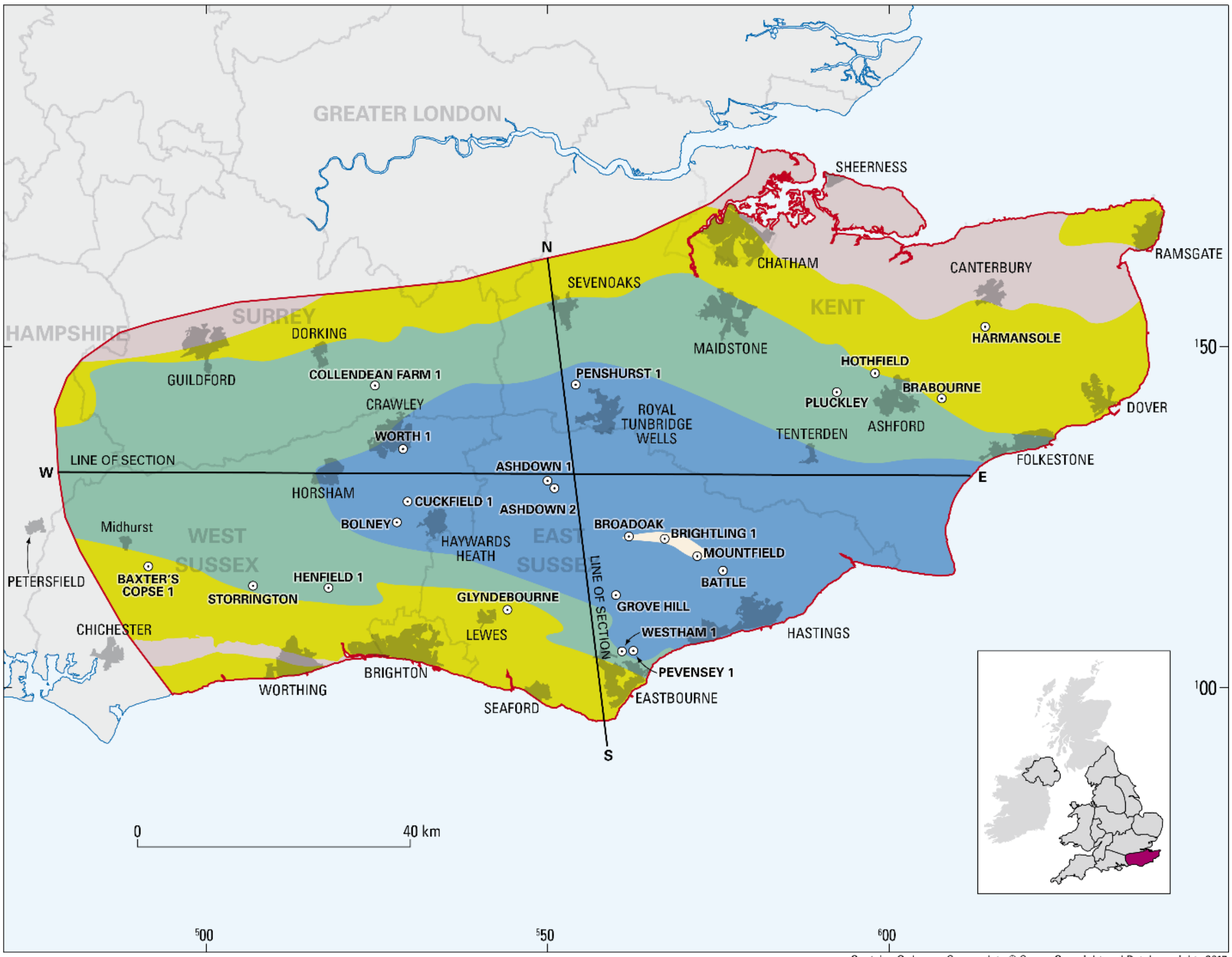
3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

The geology at surface in the region is shown in Figure 3. Figures 4 and 5 illustrate the geological variation across the region. The reader is referred to the regional summary on the BGS website (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html) for a non-technical overview of the geology of the region and to national geological screening: Appendix A (Pharaoh and Haslam, 2018) for an account of the formation and structure of the basement, and the older and younger sedimentary cover rocks of the UK.

Considering its large-scale geological structure, the Wealden region can be divided into two parts: the Weald Basin and the London platform. The greater part of the Wealden region is underlain by the Weald Basin (also known as an eastern part of the Wessex Basin) (Figures 6 and 8). The Weald Basin formed by crustal extension and regional subsidence during the late Palaeozoic and the greater part of the Mesozoic, from Permian to Cretaceous times. Then, during Late Cretaceous and Palaeogene times, the Weald Basin was laterally compressed and uplifted, forming an elongated arch- or dome-shaped structure, the Weald Anticline, that is open to the east but closed westwards (Figure 7) (Chadwick, 1986, 1993; Ellison et al., 2004; Whittaker, 1985). Within this structure, the succession of geological formations becomes generally older towards the centre, so the oldest rocks that appear at the surface in this region (the Purbeck Group) can be found in central East Sussex (Figure 3). The Weald Anticline is outlined by the Chalk Group, which underlies the North Downs, Hampshire Downs and South Downs, forming an outwards-tilted rim around the Weald. To the north, the Chalk of the North Downs is overlain by Palaeogene deposits of the London basin, of which only small southern portions occur within the Wealden region. To the south, the Chalk of the South Downs is overlain by Palaeogene deposits of the Hampshire Basin, of which only a very small eastern portion occur in the Wealden region.

The deepest parts of the Weald Basin within the Wealden region, with the thickest Mesozoic sequences (which can reach more than 2.5 km total thickness), occur in the west (Figure 4, Figure 8) (Whittaker, 1985). This means that some of the older stratigraphical divisions are found within the depth range of interest only in the east of the region, with their westward extent within that depth range generally being greatest towards the northern and southern margins of the Weald Basin.

A narrow northern area of the Wealden region, within the area of the North Downs (and the overlying Palaeogene sediments), is underlain by the southern rim of the London platform, north of a zone of major faulting and monoclinal folding (Figure 5, Figure 6). The London platform is a structural block within which older sedimentary sequences and basement rocks (Carboniferous and older rocks) occur less than about 500 m below NGS datum. This block has been an area of relative geological stability for at least 250 million years, including the period when the Weald Basin was forming. The depth to the basement increases rapidly southwards towards the edge of the London platform. In places along the southern edge of the North Downs it is already more than 1 km below ground level, and it reaches depths of several kilometres in places below the Weald Basin. Here the basement rocks have undergone periods of deep burial and deformation during the ancient earth movements of the Variscan Orogeny (Whittaker, 1985).



Age (Ma)	Map/section descriptor	Geological sub-units		Text descriptor
40–60	Palaeogene sediments	Bracklesham and Barton groups Thames Group Lambeth Group Thanet Formation		Younger sedimentary rocks
75–145	Late Cretaceous sedimentary rocks	Chalk Group		
	Early Cretaceous sedimentary rocks	Upper Greensand and Gault formations Lower Greensand Group		
		Wealden Group (High Weald)		
145–200	Mid–Late Jurassic sedimentary rocks	Purbeck and Portland groups, Kimmeridge Clay Formation, Corallian Group, Oxford Clay Formation, Oolite groups		
	Early Jurassic sedimentary rocks	Lias Group		
200–250	Triassic sedimentary rocks	Mercia Mudstone Group Sherwood Sandstone Group		
310–350	Carboniferous rocks	Warwickshire Group Pennine Coal Measures Group Carboniferous Limestone Supergroup		Older sedimentary rocks
360–420	Devonian rocks	Various sandstone, siltstones and mudstones		Basement rocks
420–500	Early Palaeozoic rocks			

Figure 3 Generalised geological map and key showing the distribution of younger sedimentary rocks, older sedimentary rocks and basement rocks in the onshore Wealden region. The inset map shows the extent of the region in the UK. See Figures 4 and 5 for schematic cross-sections. The 'Geological sub units' column is highly generalised and does not represent all geological units in the region. Stratigraphical nomenclature and lithological descriptions are simplified and therefore may differ from those used in other sections of this report. The locations of key boreholes mentioned in the text are shown by a circle and dot. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

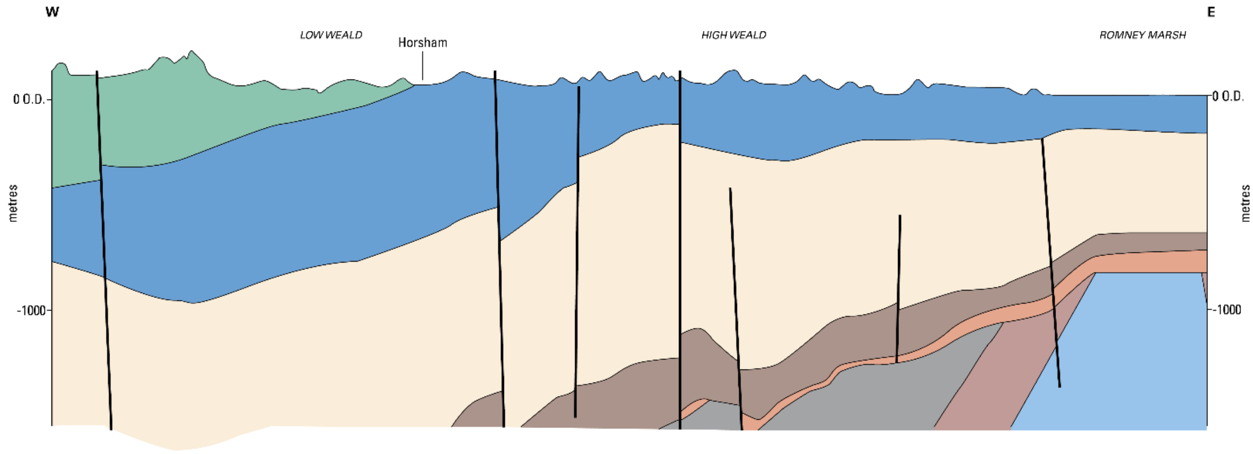


Figure 4 Schematic west–east cross-section through the Wealden region. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

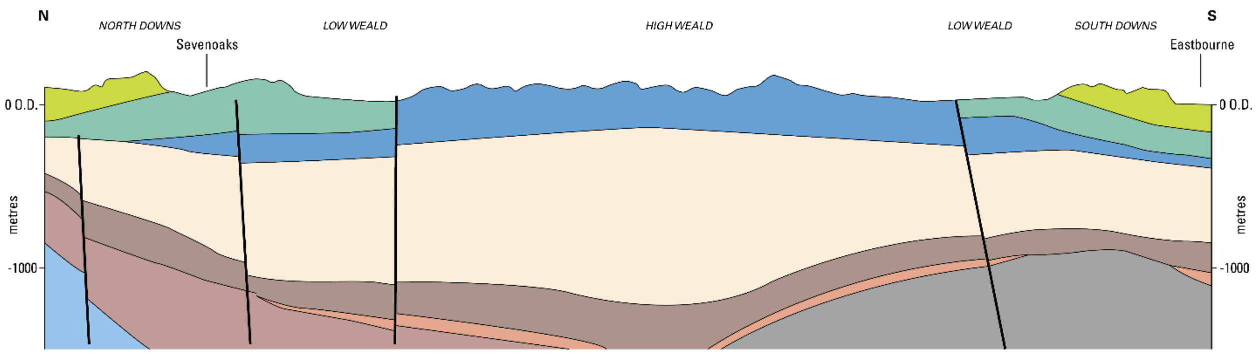


Figure 5 Schematic north–south cross-section through the Wealden region. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

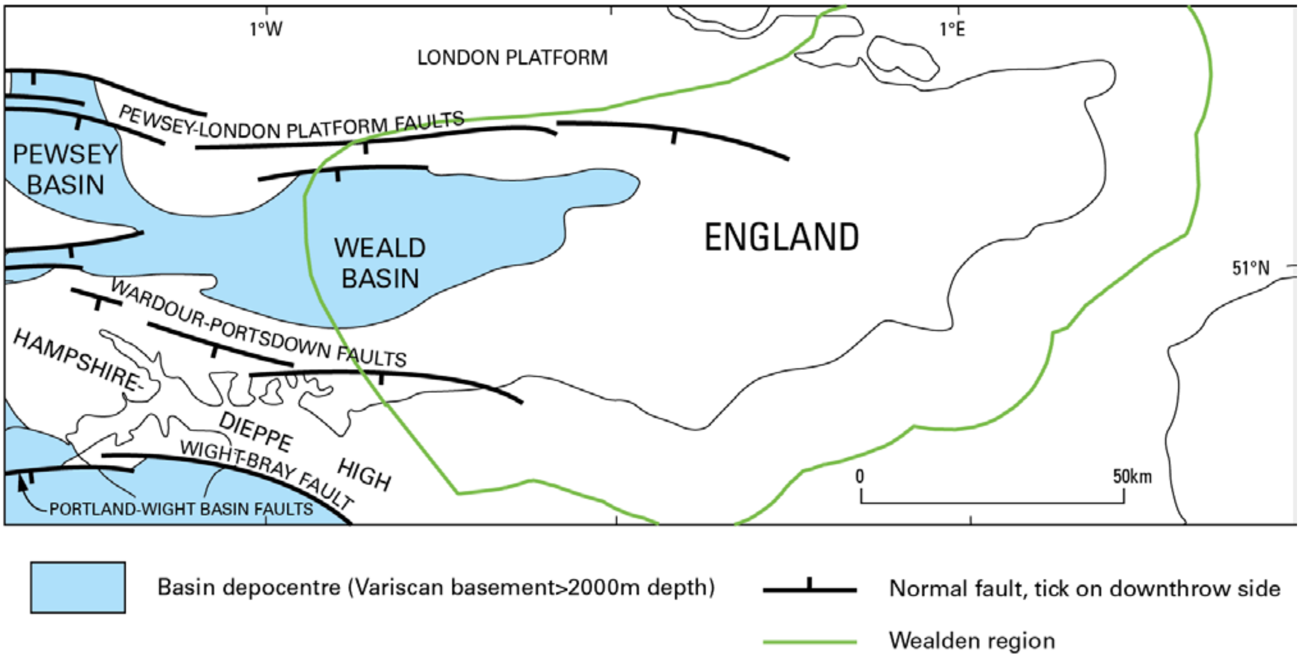


Figure 6 Position of deepest portion of Weald Basin during Permian to Early Cretaceous times. From Hamblin et al. (1992). British Geological Survey © UKRI 2018.

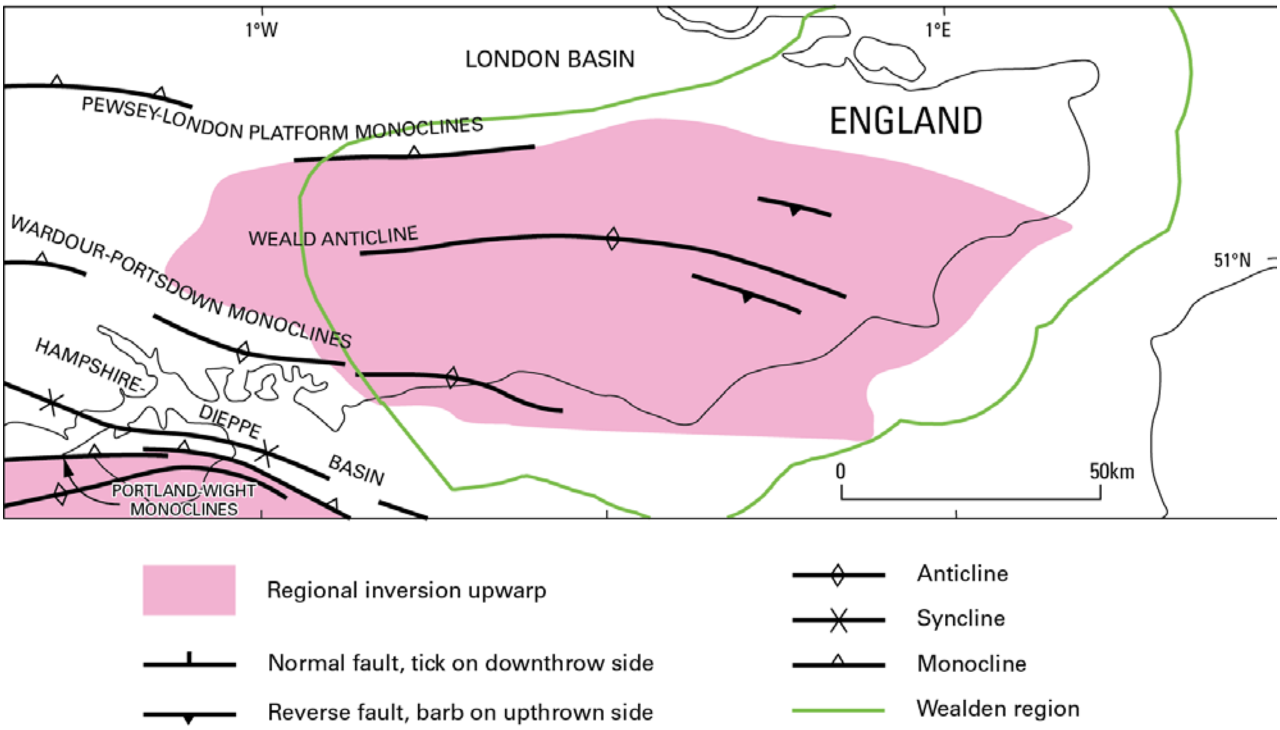


Figure 7 Main area of regional uplift during Late Cretaceous to Palaeogene times. From (Hamblin et al., 1992). British Geological Survey © UKRI 2018.

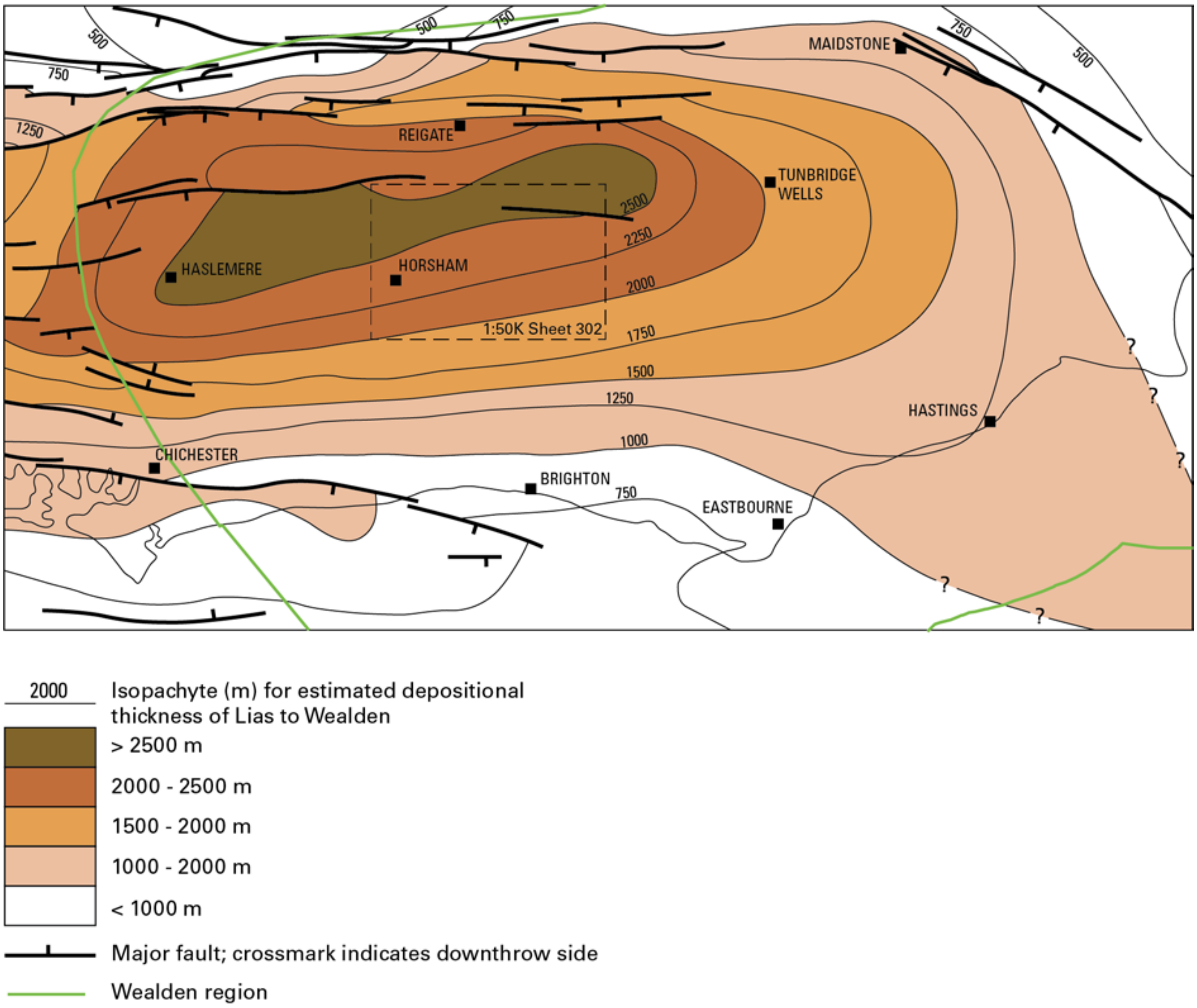


Figure 8 Estimated depositional thicknesses for the Lias Group to Wealden Group strata in the Weald Basin. Taken from fig. 3 of Gallois and Worssam (1993). British Geological Survey © UKRI 2018.

The surface geology of the Wealden region is well known from quarries and other surface excavations, sea cliffs, shallow boreholes, water wells and changes in soil composition. Surface observations, complemented by information from boreholes, allow inferences about the geological structure of the shallow subsurface. At depths greater than about 300 m below NGS datum, however, our knowledge depends largely on deep boreholes drilled in the search for water, coal, oil, gas or gypsum resources.

Oil and gas are currently extracted at several sites in the west of the region, typically from depths of more than 1 km, and other parts of the region may have oil or gas in sufficient quantities to make extraction economical. Coal was mined from depths between about 300 and 950 m at several sites in east Kent during the late 19th and the 20th centuries, with the last colliery closing in 1989 (Figure 21). Gypsum, which is used as a fertiliser and is the main constituent of many forms of plaster, is mined at depths of about 300 m in a small area in central East Sussex. There is known past shallow mining for sand, building stone, ironstone and limestone in several areas of the Weald.

Most of the deep boreholes are in either the central or western parts of the region, where prospects for oil or gas are most promising, or in east Kent within the area of the coalfield that is concealed beneath that part of the North Downs (Figures 22 and 23). Outside the area of the coalfield, there are few deep boreholes in northern Kent. Relatively few of the boreholes penetrated Triassic or older units. Although many of the deep boreholes were not cored throughout their extent, the corresponding downhole geophysical logs (together with well cuttings) generally enable detailed stratigraphical interpretations to be made. A selection of stratigraphically important boreholes, referred to in this report, is shown in Figure 3 and listed in Table 2. Uncertainties in the interpretation of individual boreholes are discussed in the reports cited in Table 2.

Hydrocarbons exploration in the Wealden region is based largely on numerous intersecting seismic reflection surveys (which provide information on the rocks by sending sound waves through the ground), together with deep boreholes that calibrate the interpretation of the seismic surveys. Numerous seismic surveys have been conducted in the area, covering most of the region except for parts of the extreme north-east (Figure 9). Some of these surveys form the basis of the maps compiled by Whittaker (1985) and also the cross-sections in the UK3D geological model. The results of the seismic surveys are complemented by interpretations of the patterns of variation in the Earth's gravity and magnetic fields shown by regional geophysical maps.

Table 2 Key stratigraphical boreholes in the Wealden region.

Borehole name	SOBI number	BGS memoir	Citation
Ashdown 1	TQ53SW 3	303 Tunbridge Wells	Bristow and Bazley, 1972
Ashdown 2	TQ52NW 12	303 Tunbridge Wells	Bristow and Bazley, 1972
Battle	TQ71NE 1	320 Hastings	Lake and Shephard-Thorn, 1987
Baxter's Copse 1	SU91NW	316 Chichester	Aldiss, 2002
Bolney	TQ22SE 17	302 Horsham	Gallois and Worssam, 1993
Brabourne (West Brabourne 1)	TR04SE 9	289 Canterbury	Smart et al., 1966
Broadoak	TQ62SW 4	319 Lewes	Lake et al., 1987
Brightling 1	TQ62SE 1	319 Lewes, 303 Tunbridge Wells	Lake et al., 1987; Bristow and Bazley, 1972
Collendean Farm	TQ24SW 1	302 Horsham	Gallois and Worssam, 1993
Cuckfield 1	TQ22NE 2	302 Horsham	Gallois and Worssam, 1993
Glyndebourne	TQ41SW 16	319 Lewes	Lake et al., 1987
Grove Hill (Hellingly 1)	TQ61SW 4	319 Lewes, 303 Tunbridge Wells	Lake et al., 1987; Bristow and Bazley, 1972
Harmansole	TR15SW 1	289 Canterbury	Smart et al., 1966
Henfield 1	TQ11SE 9	318 Brighton	Young and Lake, 1988
Hothfield	TQ94NE 1	288 Maidstone	Worssam, 1963
Mountfield	TQ71NW 2	320 Hastings	Lake and Shephard-Thorn, 1987
Penshurst 1	TQ54SW 1	287 Sevenoaks, 303 Tunbridge Wells	Dines et al., 1969; Bristow and Bazley, 1972
Pevensey 1	TQ60NW 1	319 Lewes	Lake et al., 1987
Pluckley	TQ94SW 1	288 Maidstone	Worssam, 1963
Storrington	TQ01SE 27	316 Chichester	Aldiss, 2002
Westham 1	TQ60NW 13	319 Lewes	Lake et al., 1987
Worth 1	TQ23NE 34	302 Horsham	Gallois and Worssam, 1993

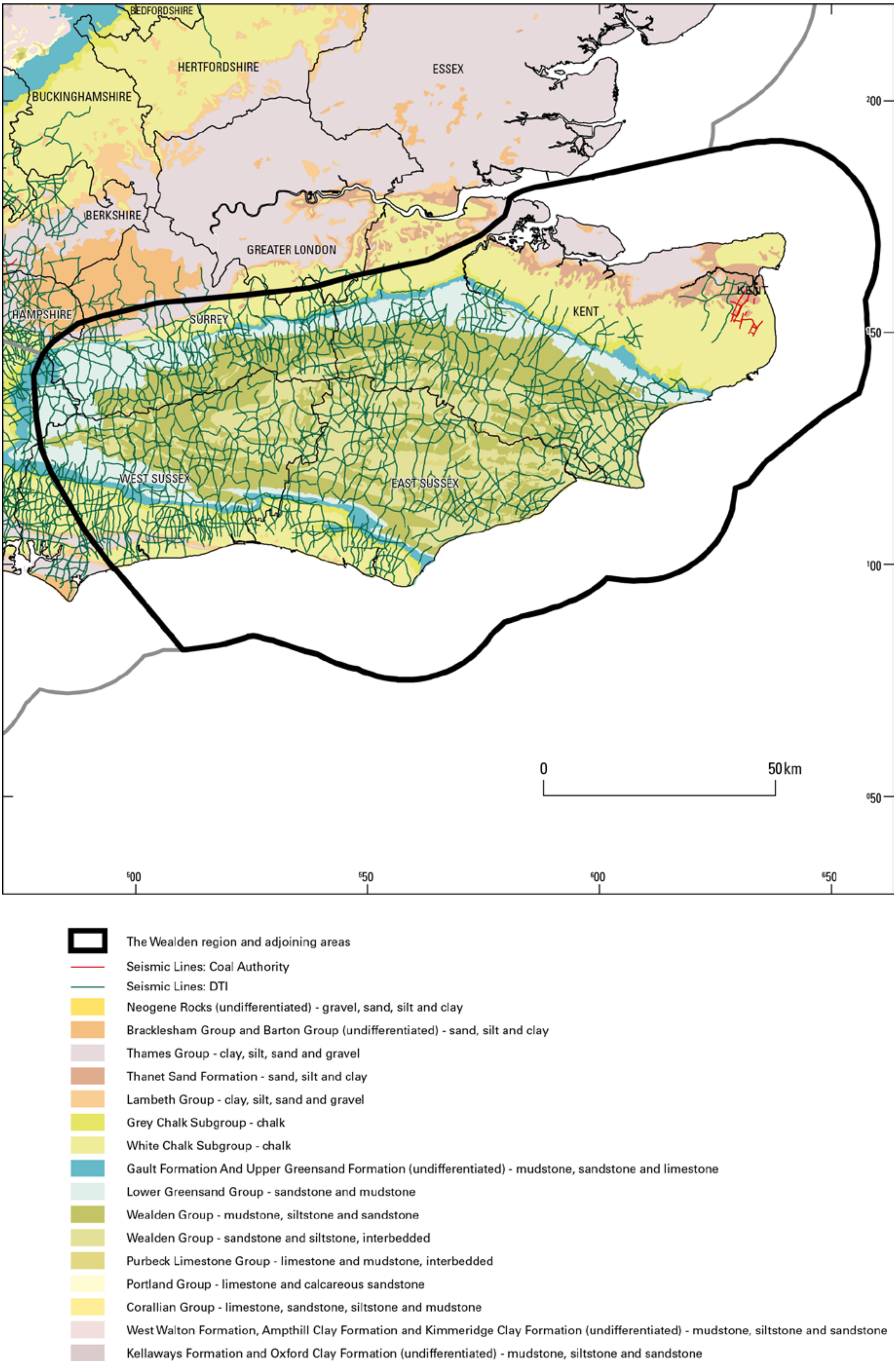


Figure 9 Distribution of seismic surveys within the Wealden region. DTI seismic lines (those derived from hydrocarbons exploration) are sourced through UKOGL (UK Onshore Geophysical Library). British Geological Survey © UKRI 2018.

The combination of surface observation, deep boreholes and seismic surveys means that, other than in parts of the North Downs of Kent, the interpretation of the geological structure of the Wealden region can be considered to be relatively well-constrained down to the base of the Lias Group (the oldest part of the succession deposited in Jurassic times), as demonstrated by the maps of Whittaker (1985). Deeper stratigraphical levels are less well-constrained but these occur within the depth range of interest only in parts of the east of the region. The geological structure of the area of the Kent coalfield is similarly well-constrained down to the productive Coal Measures. Knowledge of the deeper structure of the remaining parts of the region, essentially those parts of the North Downs outside the area of the Kent coalfield, is less well-constrained but the information that is available indicates that rock types of interest are there of rather restricted thickness and extent.

Brenchley and Rawson (2006) provide an excellent overview of the geology of England and Wales, placing individual units that occur within the Wealden region in their regional and national context. The principal BGS report on the region, the Wealden Regional Guide (Gallois, 1965) also provides a useful overview, particularly of bedrock units that occur at the surface (which are of Palaeogene or Cretaceous age), in the east Kent coalfield (units of Carboniferous age), or in rather sparse deep exploration boreholes (units of Devonian and early Palaeozoic age) elsewhere.

However, the regional guide predates most of the hydrocarbons exploration in the region, which provides a great deal of information about the buried Jurassic units, and also some about the underlying units of Triassic or greater age. For these buried units, the more recent BGS memoirs, sheet explanations, the *Atlas of Onshore Sedimentary Basins* (Whittaker, 1985) and, in particular, the local BGS Offshore regional report, *The Geology of the English Channel* (Hamblin et al., 1992) are more useful than the Wealden Regional Guide. Borehole information on the concealed Mesozoic strata in Kent was reviewed in detail by Lamplugh and Kitchin (1911) and Lamplugh et al. (1923), works widely cited by subsequent BGS reports.

Generalised descriptions of individual units, and an explanation of their place within the stratigraphical succession, are provided by the relevant BGS stratigraphical framework reports (Aldiss, 2014; Barclay et al., 2015; Barron et al., 2012; Cox et al., 1999; Hopson, 2005; Hopson et al., 2008; Howard et al., 2008; Waters et al., 2009) and by the BGS Lexicon of Named Rock Units (which should follow the stratigraphical framework reports), but these descriptions are not necessarily specific to the Wealden region.

Copies of borehole logs describing the identity or composition, or both, of the rock layers encountered (stratigraphical logs and lithological logs) are held by the BGS for many individual boreholes. Scanned images of many of these logs can be viewed online through the BGS website. For some boreholes, the BGS holds geophysical borehole logs instead of, or as well as, lithological or stratigraphical logs. These provide an indirect guide to the composition or identity of the strata intersected by the borehole, and in some cases also provide information about physical properties such as porosity. Many of the boreholes of key stratigraphical interest are described in the corresponding BGS memoirs or other reports.

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 3.

Table 3 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 WEALDEN REGION

Table 4 presents a generalised vertical section (GVS) for the Wealden region identifying the PRTIs that occur between 200 and 1000 m below NGS datum. The geological units are generally shown in stratigraphical order. However, due to regional variations, some units may be locally absent or may be recognised in different stratigraphical positions from those shown. Only those units identified as PRTIs are described. Principal aquifers are also shown and are described in Section 6.

For the Wealden region, the GVS groups the rocks of the UK into three age ranges: younger sedimentary rocks (Palaeogene to Permo-Triassic), older sedimentary rocks (Carboniferous) and basement rocks (Table 4, Column 1). The PRTIs identified in the region are predominantly lower strength sedimentary rock (LSSR) units within younger and older sedimentary rocks with small areas of higher strength rock (HSR) identified in basement rocks in the south-east of the region. There are no evaporite (EVAP) PRTIs in the region.

The Palaeogene age Bracklesham Group and Barton Group (Undivided), Thames Group and Lambeth Group are shallower than the depth range of interest and are not discussed further.

Devonian Rocks (Undifferentiated), Silurian Rocks (Undifferentiated) and, possibly, Cambrian and Ordovician Rocks (Undifferentiated) are present within the depth range of interest across large parts of central and eastern Kent and adjacent parts of East Sussex (Figures 4 and 12). Some of these potential HSRs mainly lie to the north of the cleavage belt inferred to be present to the south of the Variscan Frontal (Section 5.2) and so are excluded as PRTIs. However, areas of HSR located between Maidstone, Folkestone and Hastings (and immediately offshore of these locations) do occur within the cleavage belt within the depth range of interest and are discussed below

The PRTIs are described in Table 3 in stratigraphic 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 taken from a range of sources as described in Section 3.1 and other published sources (see references). They may include terminology or nomenclature that has been updated since those publications were released. The term ‘mudstone’ follows BGS usage to include claystone and siltstone-grade siliciclastics (Hallsworth and Knox, 1999). The location of boreholes referred to in this chapter are shown on Figure 3.

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

Three maps showing the regional distribution of PRTIs between 200 m and 1000 m below NGS datum for the three generic host rock types are provided in Figures10, 11 and 12. A summary map showing the combined lateral extent of all PRTIs is provided in Figure 13.

Table 4 Schematic GVS for the Wealden 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 10, 11 and 12 for the regional distribution of PRTIs amalgamated by host rock model (i.e. LSSR, EVAP and HSR respectively).

Geological period		Geological unit identified in NGS3D	Dominant rock type	Potential rock types of interest			Principal aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS	Palaeogene	Bracklesham and Barton groups	Clay, silt, sand and gravel	N/A	N/A	N/A	N/A
		Thames Group	Clay, silt, sand and gravel	N/A	N/A	N/A	N/A
		Lambeth Group	Clay, silt, sand and gravel	N/A	N/A	N/A	N/A
		Thanet Formation (Montrose Group)	Sand, silt and clay	N/A	N/A	N/A	N/A
	Cretaceous	Chalk Group	Soft, fine-grained limestone with flint	N/A	N/A	N/A	Chalk Group
		Upper Greensand Formation (Selborne Group)	Mudstone and silty mudstone (Gault); siltstone, sandstone (Upper Greensand)	N/A	N/A	N/A	(Upper Greensand in hydraulic continuity with Chalk Group)
		Gault Formation (Selborne Group)		N/A	Gault Formation	N/A	N/A
		Lower Greensand Group	Mudstone, silty mudstone, muddy sandstone	N/A	N/A	N/A	Folkestone and Hythe formations
		Wealden Group	Mudstone, silty mudstone, siltstone, sandstone	N/A	Weald Clay Formation, Grinstead Clay Member, Wadhurst Clay Formation	N/A	N/A
	Jur to Cret	Purbeck Group	Interbedded limestone and mudstone	N/A	N/A	N/A	N/A
	Jurassic	Portland Group	Mudstone, siltstone, muddy sandstone and thin limestone	N/A	Portland Group (mudstone-rich parts only)	N/A	N/A
		Kimmeridge Clay Formation	Predominantly mudstone, with subordinate siltstones, sandstones and limestones	N/A	Kimmeridge Clay Formation	N/A	N/A
		Corallian Group	Limestone, sandstone, siltstone and mudstone	N/A	Corallian Group (mudstone-rich parts only)	N/A	N/A
		Oxford Clay and Kellaways formations (undivided)	Mudstone, siltstone and thin silty limestone	N/A	Oxford Clay Formation, Kellaway Formation	N/A	N/A
		Great Oolite Group	Sandstone, limestone and argillaceous rocks	N/A	N/A	N/A	N/A
		Inferior Oolite Group	Limestone, sandstone, siltstone and mudstone	N/A	N/A	N/A	N/A
		Lias Group	Mudstone, siltstone, limestone and sandstone	N/A	Lias Group	N/A	N/A
	Triassic	Mercia Mudstone Group (including Penarth Group)	Mudstone, siltstone and sandstone	N/A	Mercia Mudstone Group and Penarth Group	N/A	N/A
		Sherwood Sandstone Group	Sandstone, siltstone and mudstone	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Warwickshire Group	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	N/A	Warwickshire Group	N/A	N/A
		Pennine Middle Coal Measures Formation and South Wales Middle Coal Measures Formation (undivided)	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	N/A	N/A	N/A	N/A
		Pennine Lower Coal Measures Formation and South Wales Lower Coal Measures Formation (undivided)	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	N/A	N/A	N/A	N/A
		Tournaisian–Visean rocks = Carboniferous Limestone Supergroup	Limestone with interbedded mudstone	N/A	N/A	N/A	N/A
BASEMENT ROCKS	Devonian	Early Devonian rocks (undivided)	Mudrock with siltstone and sandstone	Undivided cleaved Devonian rocks	N/A	N/A	N/A
	Early Palaeozoic	Silurian rocks (undivided)	Mudstone, siltstone, and sandstone	Undivided cleaved Silurian rocks	N/A	N/A	N/A
		Cambrian and Ordovician rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A

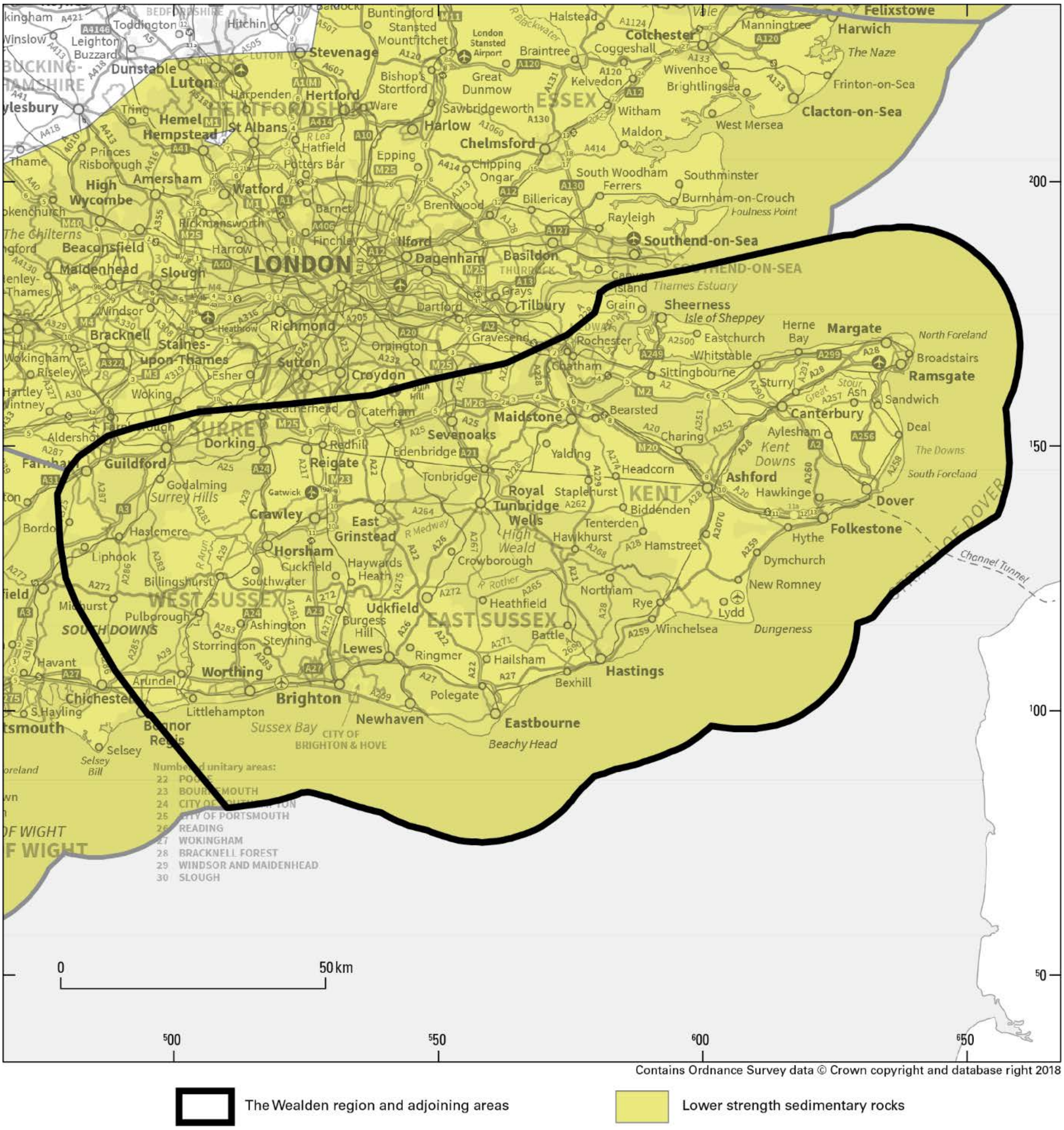


Figure 10 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Wealden region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

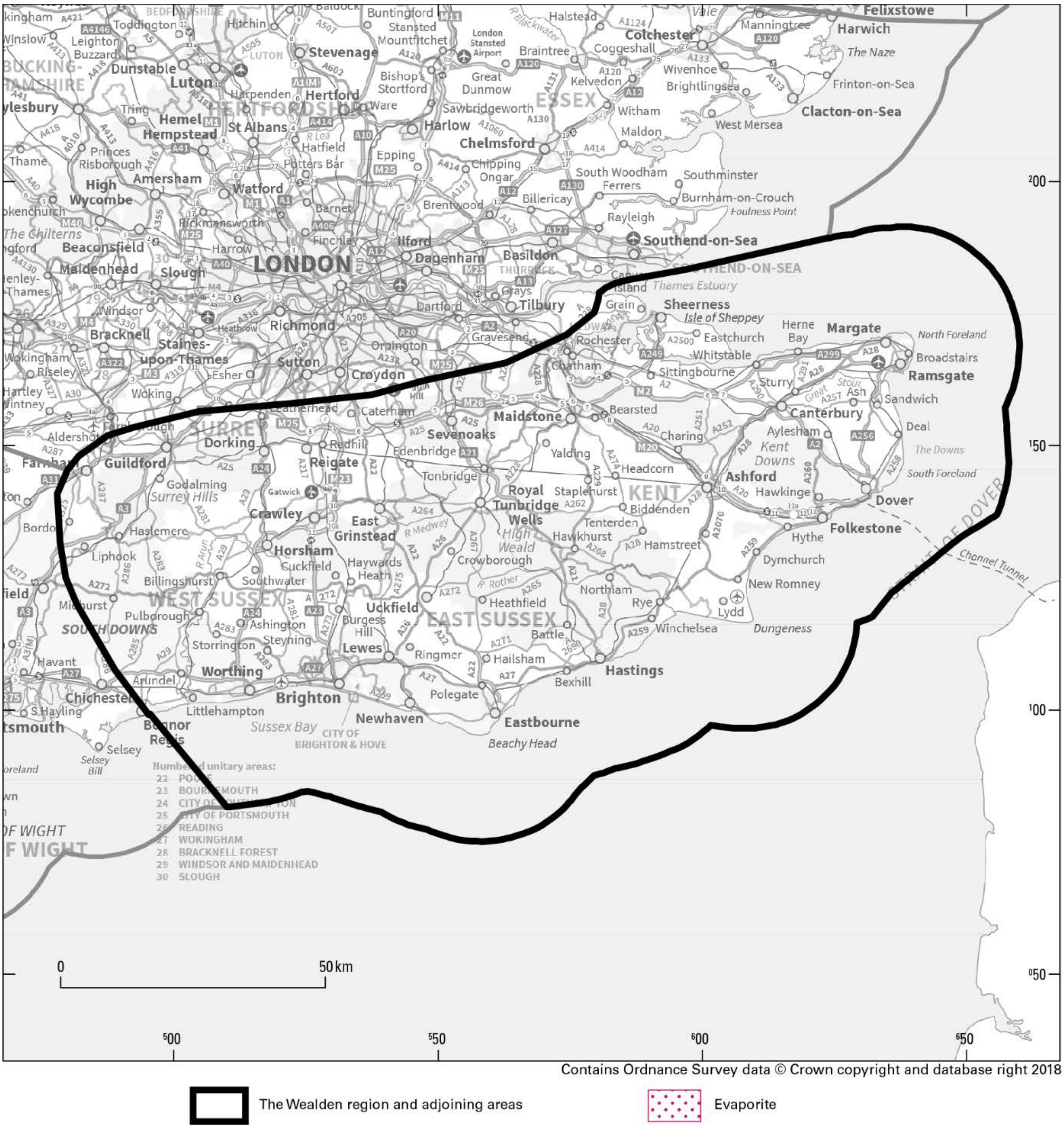


Figure 11 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the Wealden region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

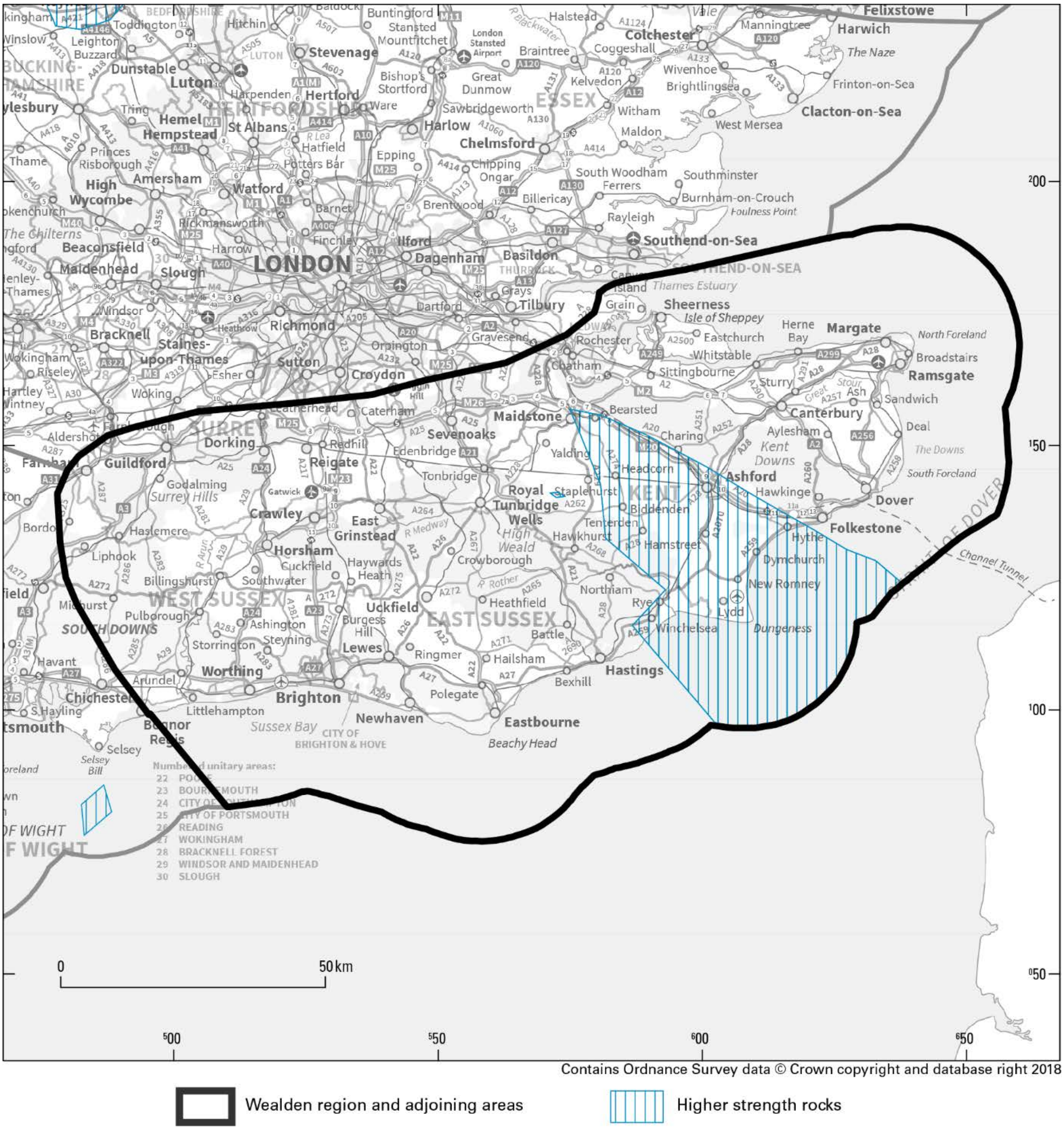


Figure 12 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Wealden region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

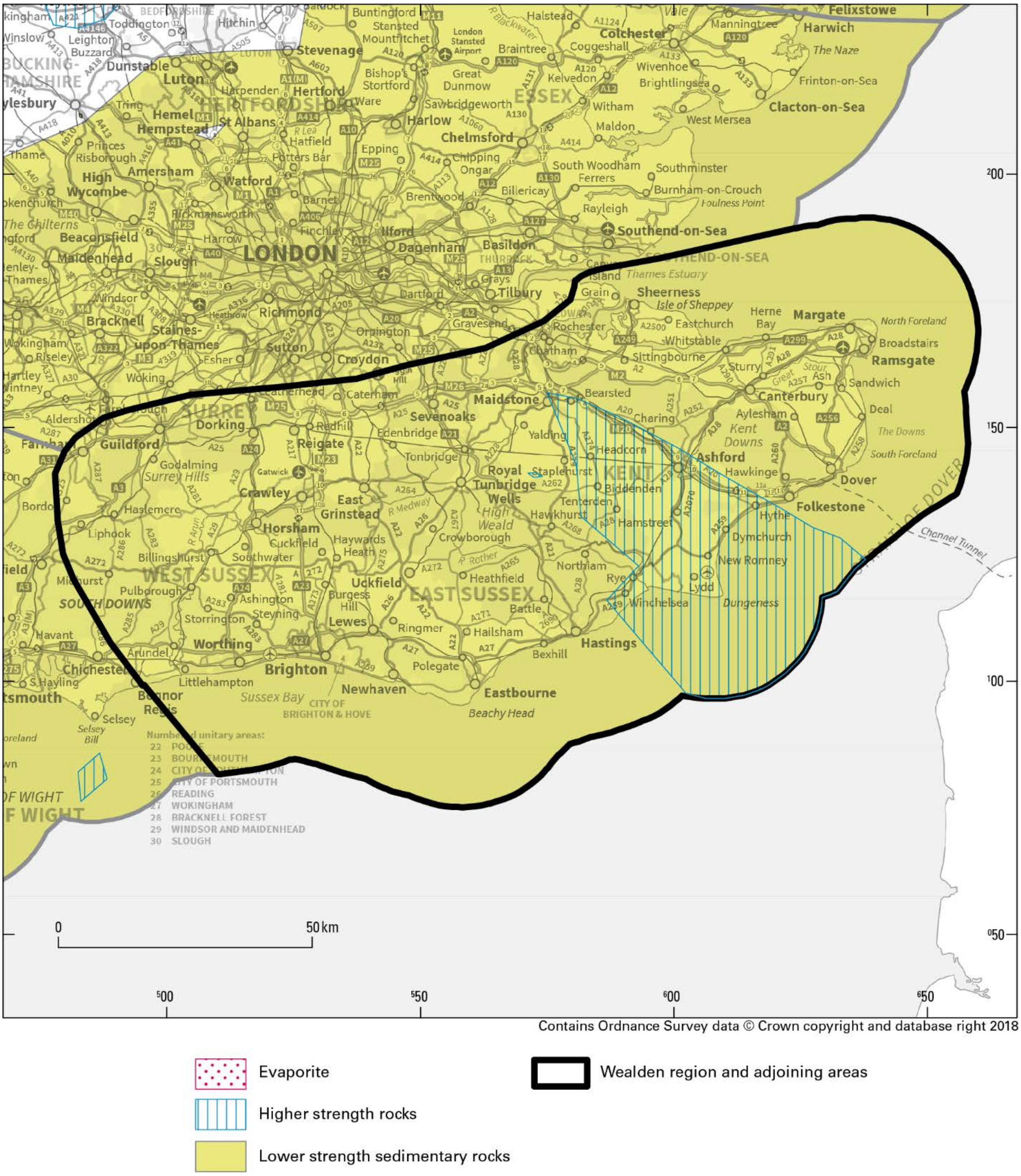


Figure 13 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Wealden region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

4.2.1 Younger sedimentary rocks

4.2.1.1 Gault Formation — LSSR

The Gault Formation is typically a thick succession of mudstone deposited on the sea floor in shallow waters at some distance from sources of land-derived sediment. In general it becomes silty and sandy upwards, and some places also laterally, passing into the Upper Greensand Formation, a silty, sandy sometimes cherty unit that represents sea floor deposition closer to the contemporary shoreline than the Gault. In other places, for example in the north-eastern part of the region, in Kent, the Upper Greensand Formation is absent (Figure 14). The Upper Greensand Formation is not a PRTI and is not described further in this report.

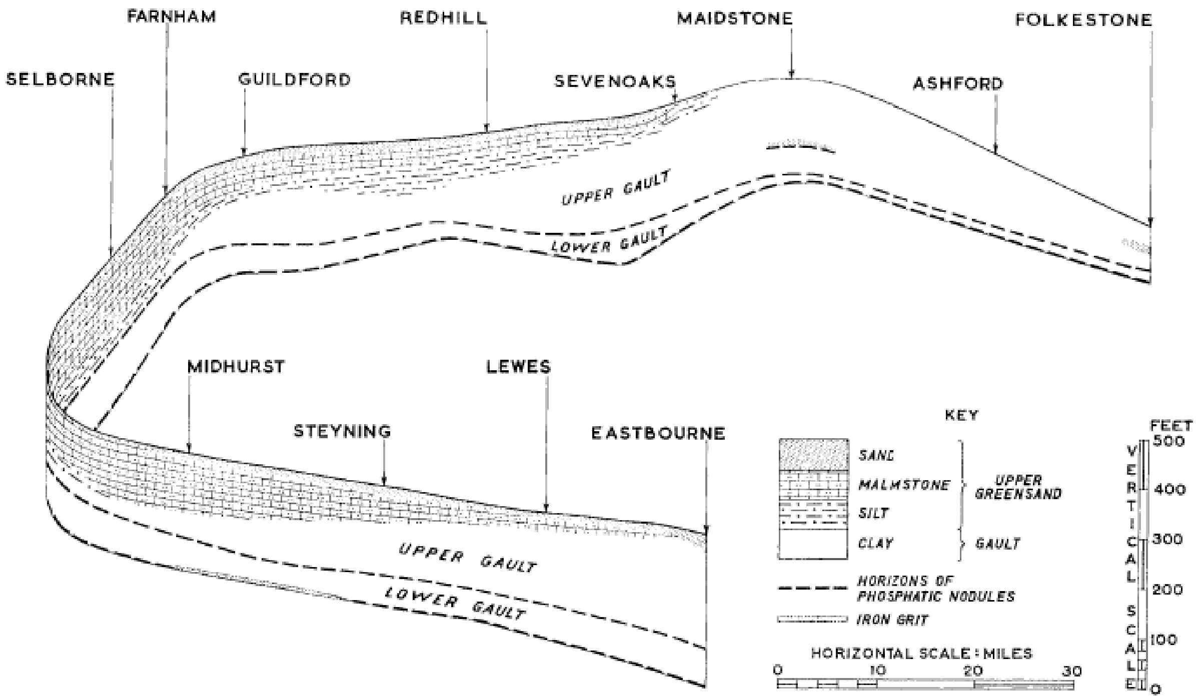


Figure 14 Ribbon diagram showing the relationship of the Gault Formation to the Upper Greensand Formation in the Wealden region. From Gallois (1965). British Geological Survey © UKRI 2018.

The Gault Formation forms a continuous outcrop around the periphery of the Weald area, at the foot of the North Downs in the north, the Hampshire Downs in the west and the South Downs in the south (Figure 3). It extends beneath the Chalk Group that forms these areas of downland but reaches depths of more than 200 m below NGS datum only towards the margins of the region, in north Kent and Surrey (close to the northern edge of the Chalk outcrop), and in Sussex and immediately adjacent parts of Hampshire (close to the coast at Eastbourne in the east, shifting towards the middle of the Chalk outcrop nearby to the west, and as far as Petersfield). It is present offshore, within the depth range of interest, both to the north and east of the Kent coast (north of South Foreland), and to the south and south-east of the Sussex coast (west of Beachy Head).

In the Wealden region, the Gault Formation typically consists of soft mudstones and silty mudstones, although the basal part is silty or sandy. Some beds are glauconitic or calcareous with layers including small phosphatic nodules. Mostly, the Gault Formation rests on the Lower Greensand Group. In north and east Kent, the Gault Formation extends further north than the Lower Greensand Group, and rests on units of Jurassic age, then (progressively further to the north) on Carboniferous, Devonian and Silurian rocks. The thickness of the Gault Formation varies locally, but there is a general thickening towards the west and south. Where it occurs within the depth range of interest the Gault Formation is about 38 m thick at Dover, thinning northwards to only 17.4 m near Ramsgate (Shephard-Thorn, 1988), between 40 and 50 m in the Faversham district (Holmes, 1981) and between about 40 and 60 m in the Chatham district (Dines et al., 1954). It is around 110 to120 m thick in deep boreholes near Guildford in Surrey (Ellison et al., 2002), between about 60 and 90 m in the Chichester district (Aldiss, 2002), and 54 m at Sompting near Worthing (Young and Lake, 1988).

4.2.1.2 WEALDEN GROUP — LSSR

The Wealden Group of the Weald Basin includes three thick to extremely thick mudstone units, comprising in upward succession: the Wadhurst Clay Formation, the Grinstead Clay Member (part of the Tunbridge

Wells Sand Formation) and the Weald Clay Formation. These are separated by thick units composed largely of sandstone.

The Wealden Group occurs at the surface throughout main part of the Weald, and is the most extensive geological unit seen at the surface in the Wealden region (Figure 3). It extends southwards beneath the Chalk of the South Downs, although it diminishes in thickness considerably and to the west of Brighton does not reach as far as the south coast. Between Brighton and Eastbourne, the Wealden Group extends a short distance offshore. It likewise diminishes in thickness rapidly northwards beneath the North Downs and in the subsurface to the east of Chatham it generally does not extend as far as the north Kent coast, other than near Margate.

The Wealden Group extends to more than 200 m below NGS datum in most of the west of the region, where it is thickest, both where it occurs at the surface and where it is concealed beneath younger units. In part of the west of the area, around Haslemere, the Wealden Group is the only PRTI within the depth range of interest. All three of the component mudstone units occur within the depth range of interest in some part of the region. In the eastern half of the region the Wealden Group thins, so although the group crops out extensively at surface, it extends down into the depth range of interest only in fairly small areas. To the east of a line through Maidstone and Brighton, probably only the Wadhurst Clay Formation occurs within the depth range of interest, and where the Wealden Group outcrop meets the coast along the English Channel very little of the unit reaches 200 m depth. The main exception is found in the far east of Kent, between Dover and Margate, but here the Wealden Group is generally less than about 20 m in thickness.

The Wadhurst Clay Formation is widely and extensively distributed at outcrop in the High Weald (Figure 3) lying between the older Ashdown Formation and the younger Tunbridge Wells Sand Formation (neither of which are described in this report). It mainly comprises dark grey mudstones and silty mudstones, some shaly, weathering to greenish-grey, ochreous-mottled and yellowish-brown clays. Thin beds of shelly limestone are present throughout. Nodular clay–ironstone beds occur particularly in the lower part of the formation, but also near the top. Thicker beds of siltstone and lenticular calcareous sandstone units are also present. The Wadhurst Clay Formation is up to about 78 m thick (at Worth, near Crawley) but is apparently rather variable, ranging down to 64.1 m elsewhere within the Horsham district, and thinning northwards to 34.1 m in the Collendean Farm Borehole just to the north (Gallois and Worssam, 1993). It can be as little as 30 m thick in the Lewes district (Lake et al., 1987) and varies from about 30 to 70 m in the Tunbridge Wells district (Bristow and Bazley, 1972) and 27 to 37 m in the Tenterden district (Shephard-Thorn et al., 1966). The greater values in the range of thicknesses found in the Sevenoaks district, about 30 to 73 m, are suspected to be a consequence of valley bulging (Dines et al., 1969). The Wadhurst Clay Formation is estimated to be about 61 m thick in the Maidstone district (Worssam, 1963).

The Grinstead Clay Member, within the Tunbridge Wells Sand Formation, is widely distributed at the surface in the High Weald, although it tends to occur in outcrops of rather limited extent. It comprises soft grey to greenish grey mudstones and silty mudstones with subordinate thin beds of siltstone, nodular clay ironstone, and shelly limestone. In most of its occurrence the Grinstead Clay Member is divided into an upper and a lower division by a bed of calcareous sandstone (the Cuckfield Stone Member). The Grinstead Clay is up to 27 m thick in the Cuckfield 1 Borehole (although this includes a central 8.3 m interval of Cuckfield Stone); nearby at Bolney it is apparently 25.5 m thick (Gallois and Worssam, 1993). It thins southwards, to about 20 m (including about 5 m of the Cuckfield Stone) in the Brighton district (Young and Lake, 1988) and disappears from the sequence in the Lewes district (Lake et al., 1987). In the Maidstone district, where the top is an eroded surface, it is about 9 m thick (Worssam, 1963).

The Weald Clay Formation mainly occurs in a single large, arcuate outcrop within the Weald Anticline. It is approximately coincident with the Low Weald, which separates the Greensand and Chalk escarpments at the periphery of the Weald from the High Weald in its core (Figure 3). The composition of the Weald Clay Formation is dominated by grey shales and mudstones, typically composed of laminated clay and silty clay, but it also includes numerous beds and lenses of sandstone and siltstone (some calcareous), pebble beds, shelly limestones and clay ironstones. It was deposited in a broad, shallow lake or coastal lagoon, with meandering rivers. More detailed descriptions are given by Worssam (1978) and Hopson et al. (2008).

In most areas the Weald Clay overlies the siltstones and silty fine sandstones of the Tunbridge Wells Sand Formation. Locally, for example around Maidstone, it rests at an erosional surface on beds as old as the Grinstead Clay Member (Worssam, 1963). It is overlain by the Lower Greensand Group.

The Weald Clay has been proved to be as much as 454 m thick around Guildford, in the north-west of the region (Ellison et al., 2002), 300 to 400 m in the Horsham district (Gallois and Worssam, 1993), thinning eastwards to up to more than 240 m around Maidstone and about 121 m at Hothfield (Worssam, 1963), and southwards to about 150 m near Lewes (Lake et al., 1987). The general trend of thickening towards the axis of the Weald, and to the west, is reflected in a general way in the width of the outcrop (Figure 3). The thickness diminishes rapidly northwards in subcrop, towards the London platform (Worssam, 1978); in the Dover area, the entire Wealden Group is less than 20 m thick (Shephard-Thorn, 1988).

4.2.1.3 PORTLAND GROUP — LSSR

The Portland Group does not occur at the surface within the Wealden region. It occurs at depth throughout the greater part of the region, mostly between 200 and 1000 m below NGS datum; it lies between the Purbeck Group (which is not described in this report) and the Kimmeridge Clay. Near the western end of the Wealden Group outcrop around Haslemere, where that unit is particularly thick, the Portland Group occurs at more than 1000 m below NGS datum. In some areas close to the eastern end of the Wealden region, it occurs only at less than 200 m below NGS datum. South-east of Chatham, beneath the North Downs, and between Brighton and Seaford, close to the Sussex coast, it is cut out of the succession by younger units of Cretaceous age. It does not extend far offshore within the depth range of interest.

The Portland Group is well exposed on the Dorset coast, west of the Wealden region. In that area, the succession is lithologically varied with sandstones, siltstones and minor mudstones giving way upwards to limestones (some cherty), dolomites and mudstones. In the Weald Basin, the Portland Group typically comprises thin siltstones, muddy sandstones and beds of phosphate nodules interbedded with mudstones. There is a thin limestone at the top of this succession, suggesting that the higher beds of the Portland Group were never deposited in this region, or were removed by erosion prior to the deposition of the Purbeck Group. In the southern part of the Weald, for example in the Lewes district, the Portland Group is represented by mudstones and silty mudstones closely similar to those of the underlying Kimmeridge Clay, although muddy sandstones are present towards the top in places (Lake et al., 1987; Young and Lake, 1988). This mud-dominated expression of the Portland Group, and the component identified as a PRTI, passes northwards into a more typical sand-rich succession (Gallois and Worssam, 1993).

Deep boreholes in the Chichester district found that the Portland Group there ranges from 4 to 46.3 m in thickness (Aldiss, 2002), in some instances lying below the depth of interest. Closer to the central axis of the Weald Basin, at Bolney, the Portland Group is 51.5 m thick (starting at 413.5 m depth) and consists of interbedded mudstones and muddy siltstones, with thin sandstone beds in the lowest part. In contrast, to the north, much of the Collendean Farm Borehole sequence, up to 54 m thick (starting at 618 m depth), consists of sandstones, with siltstone and, in the highest part, muddy, sandy limestone (Gallois and Worssam, 1993). A similar thickness, of about 57 m, was found at Penshurst, to the north-east, where most of the unit is calcareous sandstone and sandy mudstone, with mudstones down to the base passing into the Kimmeridge Clay (Dines et al., 1969). Eastwards from Bolney, the Portland Group becomes thinner (Hamblin et al., 1992), comprising about 25 m of mudstones and silty mudstones at Ashdown (Bristow and Bazley, 1972). Southwards, at Henfield, the Portland Group is represented by about 30 m of strata, including muddy and calcareous siltstones, calcareous mudstones, and muddy limestones (Young and Lake, 1988). At Grove Hill and Brightling, it comprises mudstones that are silty, calcareous, or both; siltstones; muddy sandstones, and muddy limestones. These sequences are estimated to be 24.4 m (starting at 310.9 m depth) and 31.7 m (starting at 112.8 m depth) in thickness respectively (Lake et al., 1987). The Portland Group also becomes thinner northwards, being only about 21 m thick in the Pluckley Borehole (Worssam, 1963) and less than 10 m at Brabourne, where it comprises limestones and sandstones, with some mudstone in the lower part, and still just within the depth range of interest (Smart et al., 1966).

4.2.1.4 KIMMERIDGE CLAY FORMATION — LSSR

The Kimmeridge Clay Formation does not occur at the surface within the Wealden region. It occurs at depth throughout the greater part of the region, being absent only in the extreme north-east, where it has been cut out beneath younger strata, below the North Downs. Otherwise, it lies between the Portland Group and the Corallian Group. Where it is present in this region, the Kimmeridge Clay mostly occurs between 200 and 1000 m below NGS datum. Only in a restricted area of the west, especially beneath the Wealden Group outcrop, does part or all of the unit occur at greater depths. It occurs within the depth range of interest in most of the offshore area from about Dover westwards.

At outcrop in Dorset, west of the Wealden region, the Kimmeridge Clay comprises a rhythmic succession of variably calcareous mudstones, shales, oil shales and thin limestones, with thin siltstones or silty mudstones in the lower part. In the thicker successions towards the axis of the Weald Basin, including those in parts of the Wealden region, fine-grained sandstones and siltstones occur at the base, whereas in the highest beds, thin siltstones in the south pass northwards into thicker, sandier beds (Hamblin et al., 1992). To the east the Kimmeridge Clay becomes considerably thinner, and in Kent, glauconitic sandstones are interbedded with mudstones in the lower part of the succession, which is otherwise dominated by mudstones with some limestones (Smart et al., 1966).

Deep boreholes in the Chichester district found apparently unfaulted sequences of the Kimmeridge Clay to be 234.1 and 337.4 m thick, partly within the depth range of interest (Aldiss, 2002), comparable to the 254 m found in Hampshire to the north-west (Farrant et al., 2011). Closer to the central axis of the Weald Basin at Bolney, the Kimmeridge Clay is 521 m thick (starting at 465 m depth), and at Collendean Farm it is 506 m thick (starting at 672 m depth). In the upper part of these sequences, the mudstones pass into siltstones and are interbedded with fine-grained muddy sandstones (Gallois and Worssam, 1993). Somewhat to the east, at Ashdown, the Kimmeridge Clay is 527.3 to 560.5 m thick, becoming more silty and sandy towards the base of the thicker sequence in Ashdown 1 Borehole (Bristow and Bazley, 1972). At Penshurst, to the north, it is about 444 m thick, and also has sandstones towards the base, here with some sandy limestones (Dines et al., 1969). Southwards, the unit is thinner, estimated to be about 323 m (starting at a depth of 468.8 m) at Henfield (Young and Lake, 1988), and 286.5 m thick (below a depth of 335.3 m) in the Grove Hill Borehole. It retains a thickness of 407.2 m thick (below 144.5 m) in the Brightling Borehole, further to the east. Here it is composed of siltstones, mudstones (some calcareous) and cementstones in the lower part, and probably of more or less calcareous mudstones and limestones in the upper (Lake et al., 1987). Elsewhere in eastern Sussex, the Kimmeridge Clay has been found to be 420 m thick in the Mountfield Borehole, and about 320 m at Battle. In both places the top of the unit occurs less than 200 m below NGS datum (Lake and Shephard-Thorn, 1987). In the north-east of the region, the Kimmeridge Clay is about 80 m thick at Brabourne, where it is still within the depth range of interest (Smart et al., 1966), diminishing to 13 m near Dover and eventually being cut out by the overstep of Cretaceous units beneath the North Downs (Hamblin et al., 1992; Lamplugh and Kitchin, 1911).

4.2.1.5 Corallian Group — LSSR

The Corallian Group does not occur at the surface within the Wealden region. As with the Kimmeridge Clay, the Corallian Group occurs at depth throughout the greater part of the region, being absent only in the extreme north-east, where it has been cut out beneath younger strata, below the North Downs. Otherwise, it lies between the Kimmeridge Clay and the Oxford Clay. In the central portion of the western part of the region it mostly occurs at depths greater than 1000 m. Elsewhere, it mostly occurs in the depth range of interest. It occurs in much of the offshore area from about Dover westwards to close to the western limit of the region.

At outcrop in Dorset, the Corallian Group comprises a rather varied sequence including sandstones, limestones and mudstones, some of which are calcareous. In the Weald Basin, the varied lower and upper parts of the sequence, comprising limestones, sandstones, siltstones and mudstones, are separated by a mudstone unit. Generally, this sequence thickens north-westwards from less than 80 m at Grove Hill to more than 160 m at Collendean Farm. In the more southerly parts of the region, it is almost entirely composed of calcareous mudstones with thin limestones and sandstones but as it thickens northwards, interbedded siltstones and limestones become more prominent near the base, and in the basin centre form a basal unit more than 40 m thick. The sequence then thins rapidly eastwards and northwards onto the London platform (Hamblin et al., 1992). In Kent, the Corallian Group is similar to that of Dorset (Lamplugh and Kitchin, 1911; Lamplugh et al., 1923).

At Collendean Farm the Corallian Group is 163.4 m thick (starting at 1178 m depth), comprising limestones and siltstones overlain by thick mudstones and then limestones with thin interbeds of mudstone. The topmost part is a complex sequence of limestones, mudstones, siltstones and sandstones. The Corallian Group strata at Bolney, 67.5 m thick (starting at 986 m depth), are broadly similar to the middle and upper part of the sequence at Collendean Farm, and the lower part of the sequence has probably been lost by faulting (Gallois and Worssam, 1993). It is about 138 m at Henfield, starting at about 930 m depth (Young and Lake, 1988). Eastwards, the Corallian Group is somewhat thinner, being about 115 m at Ashdown (Bristow and Bazley, 1972). To the north, at Penshurst, it is thinner still (at about 85 m, starting at about 800 m depth), again with mudstones in the upper parts (Dines et al., 1969). To the south-east, at Grove Hill and Brightling, where the Corallian is close to 76.5 m thick, starting at 621 m and 552 m respectively, it consists largely of silty calcareous mudstones and siltstones, with muddy limestones in the lower part (Lake et al., 1987). In the Dover area, the Corallian is less than 50 m thick, comprising mudstones, some calcareous, and limestones (Shephard-Thorn, 1988).

4.2.1.6 UNDIVIDED KELLAWAYS AND OXFORD CLAY FORMATIONS — LSSR

The Kellaways Formation and Oxford Clay Formation occur undivided in NGS3D, and both are identified as PRTIs.

The lower section of this undifferentiated unit, the Kellaways Formation, is a thin transitional sequence, on average 20 m thick, between the top of the Cornbrash and the base of the Oxford Clay Formation, comprising a muddy lower part (the Kellaways Clay) that passes gradually upwards into a sandy upper part (the Kellaways Sand).

The overlying Oxford Clay does not occur at the surface within the Wealden region. As with the Kimmeridge Clay, it occurs at depth throughout the greater part of the region, being absent only in the extreme north-east below the North Downs, where it has been cut out beneath younger strata. Otherwise, it lies between the Corallian Group and, with the Kellaways Formation, the Great Oolite Group (which is not described in this report). Where it is present, the Oxford Clay occurs within the depth range of interest in most of the centre, east and south of the region, and in a narrow strip at the north-west edge of the region, reaching greater depths in much of the west. It occurs in the offshore area from around Dover westwards towards the western limit of the region.

In the region, the Kellaways Clay of the Kellaways Formation comprise silicate mudstone, green, grey or blue, locally with thin beds of siltstone and sandstone, and nodules of argillaceous limestone. Typically, the Oxford Clay is composed mostly of mudstones, with some carbonaceous beds, or calcareous silty intervals that form harder beds described as ‘cementstone’. The upper parts of the formation tend to become increasingly calcareous with thin, silty limestone beds prominent at the top of the formation (Hamblin et al., 1992). Near the central axis of the Weald Basin, at Bolney, the Oxford Clay is 104.3 m thick (starting at 1053.5 m depth), comprising bituminous or calcareous mudstones with minor siltstones and silty limestones (Gallois and Worssam, 1993). It is apparently about 120 m thick in an uncored section of the deep borehole at Henfield, starting at 1049.7 m depth (Young and Lake, 1988) and about 95 m at Ashdown, starting at around 1025 m depth (Bristow and Bazley, 1972). It thins somewhat to the north, reaching only about 83 m at Penshurst, starting at 886 m depth (Dines et al., 1969), and rather more to the south, being 68.9 m thick at Brightling, starting at 629 m depth, and 66.2 m thick at Grove Hill, starting at 698 m depth (Lake et al., 1987). It also thins to the east; a maximum of 40 m has been found in the Dover area, within the depth range of interest (Shephard-Thorn, 1988).

4.2.1.7 LIAS GROUP — LSSR

The Lias Group does not occur at the surface within the Wealden region. As with the Kimmeridge Clay, the Lias Group occurs at depth throughout the greater part of the region, being absent only in the extreme north-east below the North Downs, where it has been cut out beneath younger strata. Otherwise, it lies between the overlying Inferior Oolite Group and the underlying Penarth Group (neither of which are described in this report). In the western half of the region, other than very close to the south coast and in the adjacent offshore area, the Lias Group occurs significantly deeper than the depth range of interest. Onshore, it occurs within the depth range of interest only in the east, reaching furthest westwards towards the northern and southern margins of the region. It occurs within the depth range of interest in most offshore areas between Dover and the south-western limit of the region.

The Lias Group is typically composed of predominantly calcareous, locally ferruginous or bituminous mudstones and shales, which are commonly pyritic. These types of mudstone are rhythmically and cyclically interbedded with each other and with thin limestone beds, the cyclic intervals ranging from a few metres to a few tens of metres in thickness. Thin beds of siltstone and sandstone are present at some levels (Hamblin et al., 1992). In the Wealden region, the Lias is divided into Lower, Middle and Upper units: formations named elsewhere in England are not used in systematic descriptions so far published by the BGS.

The Lias Group is about 480 m thick in the Bolney Borehole, being sandy in the lowest 50 m, but it occurs there at depths greater than 1400 m (Gallois and Worssam, 1993). In the Ashdown 2 Borehole it is 394 m thick (below about 1320 m depth) (Bristow and Bazley, 1972) and continues to thin eastwards, and also southwards and northwards. At Henfield it is about 242 m thick (starting at a depth of 1248 m) (Young and Lake, 1988). At Grove Hill the Lias Group is about 167 m thick, below a depth of 888 m, whereas nearby at Brightling, it is about 282 m thick, starting at a depth of 856 m, with much of it being fault-repeated below 1138 m depth (Lake et al., 1987). At Brightling, Grove Hill, Henfield and Bolney, the Upper Lias is an upwards-coarsening sequence, grading upwards to very fine-grained sandstone (Hamblin et al., 1992). To the north at Penshurst, the Lias Group is about 292 m thick (starting at 1116 m depth); it includes sandstones, siltstones, sandy ironstones and limestones (Dines et al., 1969). Further east, the Lias thins dramatically as the lower beds are overlapped onto the London platform: at Brabourne it is probably about 43 m thick (within the depth range of interest), with a thin basal muddy sandstone (Smart et al., 1966). Interbedded limestones come to dominate the Lias succession, as in the Dover area where several of the coal exploration boreholes showed that it is there less than 7 m thick, although still within the depth range of interest (Shephard-Thorn, 1988).

4.2.1.8 MERCIA MUDSTONE GROUP AND PENARTH GROUP (UNDIVIDED) — LSSR

The Mercia Mudstone Group and the unconformably overlying Penarth Group are modelled as one combined unit in NGS3D. The Mercia Mudstone Group and Penarth Group do not occur at the surface within the Wealden region. As with the Kimmeridge Clay, they occur at depth throughout the greater part of the region, being absent only in the north-east, where it has been cut out beneath younger strata of the Lias Group, below the North Downs, and locally elsewhere. Otherwise, they lie between the Lias Group and basement rocks of Palaeozoic age, occurring at less than 1000 m depth only in the eastern part of the region, almost entirely east of a line between Brighton and Maidstone, with this depth extent (like that of the Lias Group) being maintained furthest westwards towards to the northern and southern limits of this area. The Mercia Mudstone Group and overlying Penarth Group occur within the depth range of interest offshore between Hastings and Folkestone, with a restricted occurrence south of Beachy Head.

In general, the Mercia Mudstone Group consists of red mudstones, in some marginal areas passing into sandstones, breccias and conglomerates. The limited available borehole evidence suggests that such marginal facies occur, at least locally, in the east of the Wealden region. The mudstones tend to be silty and are locally calcareous, with thin sandstones. They commonly contain gypsum and anhydrite. Halite also occurs in what were the deeper parts of the depositional basins (Hamblin et al., 1992) and so, if present within the Wealden region, is likely to occur only in the west and below the depth range of interest.

The composition of both the Mercia Mudstone Group and the Penarth Group within the Wealden region is known only from rather sparse borehole evidence, although its distribution can be expected to be reasonably well constrained by seismic surveys. The thickest known occurrence of the Mercia Mudstone Group in the Wealden region is an incomplete sequence of 106 m (starting at 1710 m depth) found in the Storrington Borehole in the south-west, where it consists of mudstones and siltstones (Aldiss, 2002). The group thins markedly towards the east, with an interval of about 66 m (below a depth of 1490.5 m) in the Henfield Borehole thought to extend from the Mercia Mudstone Group up into the lowest Lias Group (Hamblin et al., 1992; Young and Lake, 1988). The strata here, and also further east at Brabourne (where they are within the depth range of interest), include breccias and conglomerates containing limestone fragments of possible Carboniferous age (Smart et al., 1966). Limestones, cherts and marls of unproven age found below 1054 m depth in the Grove Hill Borehole may also represent the Mercia Mudstone Group or the Penarth Group, or both (Hamblin et al., 1992). Incomplete sequences of mudstones in the Mercia Mudstone Group were found in the north-west of the region, near Guildford, but these also are deeper than the depth range of interest (Ellison et al., 2002).

4.2.2 Older sedimentary rocks

4.2.2.1 WARWICKSHIRE GROUP — LSSR

The Warwickshire Group does not occur at the surface within the Wealden region. It is largely confined to the extreme north-eastern part of the region, where it is proved in the area of the concealed Kent Coalfield, beneath the eastern end of the North Downs (Figure 23). The NGS3D model shows a further thin, partly fault-bounded, localised occurrence south of Maidstone and east of Tunbridge Wells, at a depth of a little more than 1000 m. Other instances might be present elsewhere in the region but if so, they too are likely to lie below the depth range of interest.

The Kent coalfield has the form of a basin-like downfold or trough, elongated from west-north-west to east-south-east (Shephard-Thorn, 1988) in which the strata of the Warwickshire Group are underlain and surrounded by progressively older Carboniferous and Devonian strata (Whittaker, 1985). Here the Warwickshire Group is present within the depth range of interest, underlying a relatively thin succession of Mesozoic units. These include the Mercia Mudstone Group in the southernmost part of the coalfield. The Warwickshire Group is then successively overlapped northwards by younger strata of the Lias Group, the Inferior Oolite, the Great Oolite, the Wealden Group, the Lower Greensand Group and the Gault. It overlies Coal Measures formations similar to those in the South Wales coalfield. In the past, these have been mined for coal at several locations in east Kent (Shephard-Thorn, 1988).

In Kent, the Warwickshire Group corresponds to the ‘Sandstone Division’ of earlier descriptions. It comprises up to 670 m of sandstones with some sandy shales and six main coal seams (Gallois, 1965; Hamblin et al.,1992; Shephard-Thorn, 1988). Its distribution is fairly well known from boreholes sunk to investigate the underlying productive Coal Measures.

4.2.3 Basement rocks

4.2.3.1 Undivided Devonian and Undivided Silurian rocks — HSR

Devonian rocks are present within the depth range of interest in the north and east of the Wealden region, and in the southern part of the region between Folkestone and Hastings. However, in the north and east of the region the Devonian strata are dominated by sandstones and are north of the Variscan cleavage belt and therefore are not included as a PRTI.

South of the Variscan front, the succession is believed to pass to marine, mudstone-dominated successions, and similar marine strata are present within Devonian and Silurian successions (Gallois, 1965), although, uncertainty on the nature of these rocks increases southwards. The Devonian succession is proved in a borehole at Brightling (East Sussex) comprising brown shales, thin micaceous sandstones and mudstones (Gallois, 1965). The Silurian strata in the region typically comprise grey mudstones and siltstones, commonly red, purple or green stained (Gallois, 1965). The thickness and lateral heterogeneity of these units is unknown. During the late Carboniferous Variscan deformation event these strata (both Devonian and Silurian) were deformed and the mudstones are likely to have developed a cleavage within the southern part of the region, and it is here that the units are recognised as PRTIs.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in the Wealden region and shows their surface extent on a map (Figure 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 effect on the uniformity and predictability of rocks and groundwater at a scale of relevance to a GDF.

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

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

Areas of folded rocks are considered to be important in a heterogeneous body of rock, such as interlayered sandstone and mudstone, where the rock mass has complex properties and fold limbs dip at steep angles, potentially resulting in complex pathways for deep groundwater. Where folding occurs in relatively homogeneous rock there is little change in the bulk physical properties and therefore there is less impact on fluid pathways. Hence, areas of folded rocks are defined as those where folding is extensive and/or where folding results in steep to near-vertical dips in a heterogeneous rock mass of strongly contrasting physical properties at a national screening scale of 1:625 000 (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 surface and subsurface structure and rock 'units' of the Wealden region can be described in terms of three major structural cycles and mountain building episodes (orogenic cycles) that affected the region and surrounding areas: the Caledonian, Variscan and Alpine orogenies (see Pharaoh and Haslam, 2018) for an overview of the tectonic evolution of the British Isles).

Much of the Wealden region and the adjacent Hampshire Basin region are underlain by the Variscan fold belt, affecting older (late Palaeozoic and older) rocks and bounded in the extreme north-west and north-east by the Variscan foreland, forming part of the Caledonian basement beneath these areas and comprising Precambrian rocks of the Midlands massif or microcraton (MM; Smith et al., 2005; Lee et al., 1990; Lee et al., 1991; Chadwick et al., 1989). The boundary is marked by the Variscan Frontal Thrust zone (Chadwick et al., 1989; Chadwick and Evans, 2005). For the purposes of this section, it is useful to refer to groups of strata as follows:

- Younger cover (Permo-Triassic to Cenozoic: equivalent to younger sedimentary rocks in Figure 3 and Table 4)
- Older cover ('foreland' Carboniferous in the far north and north-east of the region, north of the Variscan foreland: equivalent to older sedimentary rocks in Figure 3 and Table 4)
- Variscan basement (deformed Precambrian to Carboniferous, south of the Variscan foreland: equivalent to basement rocks in Figure 3 and Table 4)
- Caledonian basement (Precambrian to early Palaeozoic rocks, north of the Variscan foreland: equivalent to basement rocks in Figure 3 and Table 4)

The Variscan Orogeny was largely responsible for, and gave rise to, the main structural elements that controlled the subsequent Mesozoic and Cenozoic development of the region and the structures now seen at crop and imaged in the subsurface on seismic reflection data.

A large part of the region is underlain by late Palaeozoic strata that were strongly deformed during the Variscan Orogeny and which culminated in end Carboniferous times, giving rise to large-scale folding and the development of several major southward-dipping thrust zones (notably the Variscan frontal and Wardour thrusts). The thrusts dip southwards and are roughly planar to a depth of at least 15 km, beneath which they are thought to lose their identity within the lower crust (Whittaker, 1985; Chadwick, 1986, 1993).

The Variscan Frontal Thrust zone crosses west–east beneath the northern limits of the region in the general Guildford–Dorking–Biddenden areas, and then swings south-eastwards through the Maidstone to Ashford areas, crossing the coast near Folkestone, and extending south-eastwards across the English Channel, linking with the Faille du Midi fault zone in northern France. The region thus straddles two main geological or tectonic domains, relating to the Variscan orogen.

The Variscan foreland: an area of relatively weakly deformed foreland basement rocks to the north of the Variscan Frontal Thrust, forming part of the London–Brabant massif and underlying the northern and north-eastern parts of the Wealden region. The area was a dominant structural high area for much of Phanerozoic times. Within the Wealden region, pre-Permian strata occur at depths of around 400 to 1200 m and are disposed about a gentle, poorly constrained north-north-west-trending syncline. The early Palaeozoic rocks show high dips, cleavage and low-grade metamorphism. The youngest pre-Permian strata preserved in the region are of Westphalian A–C age, deposited in foreland basins to the north of the rising Variscan fold belt, and now preserved in the core of a gentle synclinal fold, the axis of which runs north-west to south-east through Kent from Dover on the coast. Coal was mined at four collieries (Chislet, Betteshanger, Snowdown and Tilmanstone).

The foreland area is generally structurally simple with little known major faulting. North-east of the Maidstone–Ashford line, east–west trends dominate in the Upper Cretaceous and Tertiary strata (e.g. Worssam, 1963). East–west faulting and gentle anticlinal folding is observed in the Cliffe area on the borders with the Thames region, and in the 'Thanet lineament' (complementary to and slightly north of the Thanet syncline) in the north-east of the region. A strong consistency of the 'structural grain' is evident but the formation of post-Variscan graben, or even fault movement, may be very localised in extent (Lake, 1975).

The Variscan fold belt (Variscides): occupies the area to the south of the Variscan Frontal Thrust zone. This area is largely coincident with a major Mesozoic structural and depositional province, generally referred to as the Wessex–Weald basin, which extended eastwards across southern England and southwards, offshore into the English Channel basin. The Variscan fold belt is dominated by a series of east-west-trending extensional structures that were controlled by the deeper Variscan thrusts. The extensional structures controlled the subsequent Cenozoic structural and depositional evolution of the region during the Alpine compressional event(s).

The structures recognised across the Wealden region and affecting the younger (Mesozoic and Cenozoic) rocks were formed during Mesozoic extension and Cenozoic compressional phases. It is only relatively recently, during hydrocarbon exploration and with the advent of seismic reflection data, for which there is a dense cover over most of the region, that the true subsurface nature and origin of the Cenozoic folds have been revealed and understood.

Extensional reactivation of the Variscan thrusts controlled the structural evolution of the region during Permian to Cretaceous times as a series of normal faults developed, which are usually synthetic (downthrown to the south) to the underlying thrust, though significant antithetic normal faulting can also occur. These defined a major extensional province across much of southern England: the Wessex–Weald basin and southwards, offshore into the English Channel basin. In the shallower section a series of steeper, predominantly downthrown-to-the-south, short-cut normal faults were initiated, facilitating the collapse of the hangingwall block to form a series of faulted intrabasinal highs and graben/half-graben within which smaller sedimentary sub-basins developed. Within the main Weald Basin, the most notable sub-basin is the south-eastern extension of the Cranborne–Fordingbridge high, the Hampshire–Dieppe high, in the south-west of the region. These structures strongly influenced and controlled the distribution of younger cover strata (Stoneley, 1982; Whittaker, 1985; Chadwick, 1986; Lake and Karner, 1987). During periods of active crustal extension, syndepositional movement on the predominantly southerly downthrowing major normal faults resulted in relatively thick sequences of sediment being deposited on the downthrown (hanging wall) sides, with relatively thin sequences on the upthrown (footwall) sides of the major faults. Within the region, changes in the thickness of the strata across the main faults indicate major periods of active faulting during Early Jurassic and Late Jurassic times and during deposition of the Wealden ‘Group’ of the Early Cretaceous. Episodes of fault movement were interspersed with periods of regional subsidence when sediments thickened more evenly towards the depocentres and onlapped across the intervening highs.

The final major period of extensional fault movement in the Wessex–Weald basin took place in Early Cretaceous times. This resulted in the accumulation of thick sequences of Wealden ‘Group’ sediments in the main fault-bounded troughs in the eastern Wessex–Weald basin, while the intervening exposed highs suffered varying degrees of erosion. Although the mid to Late Cretaceous is commonly regarded as being a relatively quiescent period tectonically, some local variations in the Early Cretaceous and Chalk sequences reflect a degree of tectonic control (Mortimore and Pomerol, 1997).

Deposition in Paleocene to Oligocene times was followed by the onset of a compressive tectonic regime during Oligocene to Miocene ‘Alpine’ earth movements (Lake and Karner, 1987; Chadwick, 1993; Chadwick and Evans, 2005). Available evidence suggests that whilst minor episodes of inversion affected the Wessex–Weald–Channel basin from Late Cretaceous times onwards, coeval with the ‘Laramide’ inversions of northern Europe, the major basin inversion did not take place until Miocene times, associated with ‘Helvetic’ Alpine and Pyrenean orogenic events. This compression effectively reversed the sense of movement on the major syndepositional normal faults within the Wessex–Weald basin, leading to basin inversion and the formation of general basin upwarps and more localised, tighter, northerly verging inversion fold pairs, including monoclines with steep to overturned northern limbs along the former syndepositional faults. Uplift may be >1500 m in places. Subsequently, erosion has unroofed these inverted basins, giving rise to the present-day landscape and, together with the varying degree of reversal along faults, can produce markedly different juxtapositions of rock. Importantly, following this main period of compression, a pervasive north-west-trending mesofracture system was established, cutting the Late Cretaceous and Palaeogene rocks and east–west-trending inversion flexures of southern England and northern France. The north-west-trending fractures and lineaments are thought to be neotectonic, resulting from a period of north-east to south-west regional tension generated during the late Neogene to Holocene ‘Jura’ phase of north-west to south-east Alpine convergence (Bevan and Hancock, 1986).

5.3 MAJOR FAULTS

The major faults selected from analysis of the UK3D model and supporting data in the region (Figure 15) exhibit a variety of orientations and evolutionary histories, as a consequence of the complex Palaeozoic to Cenozoic structural history, described in Pharaoh and McEvoy (2018). Their presence affected sedimentation in Mesozoic and later times and also controlled the position and alignment of folds and faults visible at the surface.

Across the Wealden region, discrete, generally east–west-trending structural zones of folding and faulting, separated by wider, less deformed areas, are identified. Five main structural zones are recognised (in part after Lake, 1975): Farnham–Guildford–Dorking–Biddenden; Benenden (also known as the Hog's Back Fault); the Purbeck inliers; Burgess Hill–Pevensey (Sayers Common–Isfield–Horsebridge Fault), and the Portsdown–Middleton structures. They are related to and reflect pre-Permian basement structures, some of which extend offshore and have counterparts in France. The influence of structural control from the underlying basement and, frequently, a comparable displacement history reflect the response of similarly orientated fault planes to extension or compression in the contemporaneous regional stress field.

In the following description, the major, arcuate fault zones and associated narrow belts of folding are described in terms of a series of faults with a dominant orientation and displacement direction, which were themselves controlled by similarly trending, southerly dipping Variscan thrusts in the pre-Permian basement. The major fault zones are predominantly downthrown to the south normal faults, such as the Pewsey–Southern London Platform Margin and Wardour–Portsdown faults, which cross the adjacent Hampshire Basin region and enter the western areas of the current region. They do, however, also include a number of antithetic, downthrown to the north faults, which together form narrow, generally east–west graben and some associated horst structures. As this region is occupied by 'cover' sequences at crop, folding is usually related to inversion of the cover sequence and localised to the major fault zones, which have suffered such inversion and are associated with important arcuate belts of inversion folds, such as the Portsdown–Littlehampton and Purbeck inliers of Sussex (e.g. Howitt, 1964). The main faults developed within the depth range of interest in the region have east and north-west trends.

Beneath the region two thrusts are identified from seismic refection data: the Variscan frontal thrust zone and the Wardour Thrust, which formed in latest Carboniferous times and postdate strata of Westphalian age. The Wardour Thrust probably developed first and initially marked the northern limit of the Variscan fold belt. Subsequently, foreland-directed thrusting propagated northwards with the development of a low angle sole thrust, the Variscan Frontal Thrust zone (e.g. Chadwick, 1986). These basement thrust zones were reactivated during episodes of Permian and Mesozoic crustal extension and controlled the development of important, dominantly downthrown to the south, normal fault zones above the thrusts and which now cross southern England. They formed as classic hanging-wall, short-cut normal faults, defining a series of generally east trending, *en échelon*, fault-controlled sub-basins or half-graben, with intervening 'highs' and over which subsidence was less marked. The fault zones may cross into the adjacent regions. The following account describes the more important fault zones of this type in the region.

In addition to the main east–west trending Variscan thrusts in the pre-Permian basement, a system of widely spaced, subvertical, north-west-trending, dextral wrench or transcurrent faults formed across southern England contemporaneously with, or shortly after, the thrusts. These structures can be seen in the exposed basement massifs of south-west England and define structural domains, offsetting the east–west-trending faults in the Variscan, Exmoor and Foreland tracts. They also underwent reactivation and affected Permian and Mesozoic basin development, sediment thickness and distribution. Whilst evidence for such fault zones is not clear at crop in the region, the presence of such faults concealed in the subsurface cannot be ruled out, with perhaps the south-eastern extent of the Maidstone–Ashford and Biddenden fault zones being at least in part transcurrent in nature.

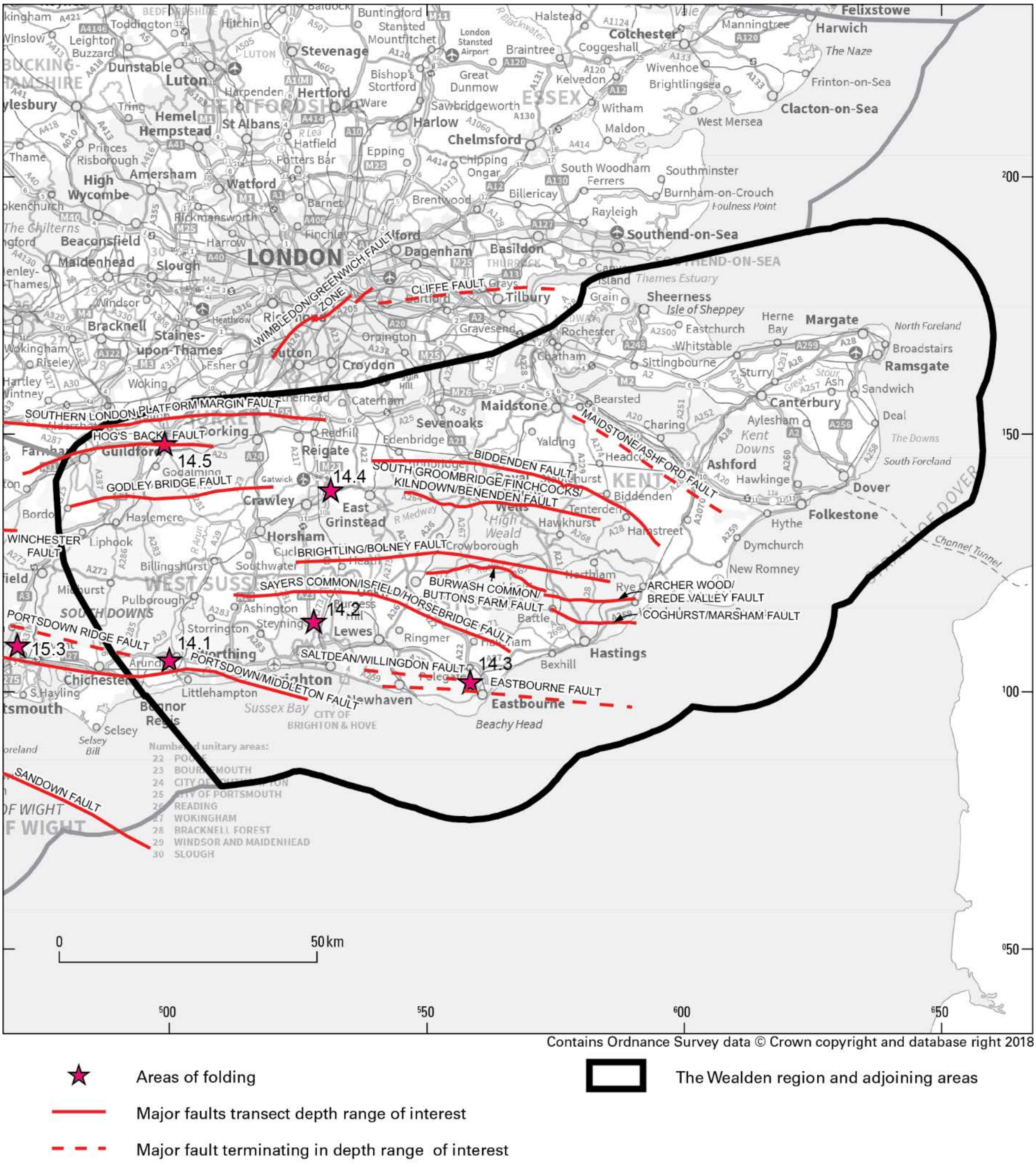


Figure 15 Major faults and areas of folding in the Wealden region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

5.3.1 Vale of Pewsey–Pewsey Basin–Southern London Platform Margin faults

Running across the north of the Wealden region, the Southern London Platform Margin and Hog's Back faults are a complex, braided series of arcuate, predominantly east–west-trending, Permian and Mesozoic syndepositional normal faults, which have suffered reversal of throw (inversion) during Alpine compression. They mark the northern margin of main Mesozoic Wessex and Weald extensional basin development and the southern limits of the London–Brabant massif. They are part of a major fault system that extends over 165 km from Westbury in the west, eastwards along the northern areas of the adjacent Hampshire basin region towards Basingstoke just to the north-west of the Wealden region: these are known as the Vale of Pewsey–

Pewsey Basin–Southern London Platform Margin faults (Pewsey–Southern London Platform Margin faults). These major fault zones were controlled by the extensional reactivation of the Variscan front thrusts within the basement.

The Pewsey–Southern London Platform Margin faults extend across the northern limits of the Wealden region, through and to the north of the Guildford area, with up to 700 m of net normal displacement. The Southern London Platform Margin fault zone is approximately 69 km in length with 400 to 600 m displacement (Whittaker, 1985). The Hog’s Back Fault to the south is approximately 40 km in length, with up to 600 m displacement and suffered greater reversal than the Southern London Platform Margin Fault. The Southern London Platform Margin and Hog’s Back faults were fairly inactive in Permo-Triassic times, but by the Early Jurassic started to control development of the Weald Basin. Through the central and eastern parts of the region, to the east of the mapped position of the major fault, the faulting is relatively poorly defined with no major faults mapped. However there is probably a series of *en échelon* faults with only minor displacement, which link the Southern London Platform Margin Fault and Hog’s Back Fault in the west to the concealed north-west to south-east-trending Maidstone–Ashford fault zone. It is also noteworthy that regional upwarp of the Weald Basin, forming the gentle Weald Anticline (strictly an anticlinorium), was most severe over its central and eastern parts, where the northern bounding faults are less distinct. Basin inversion was therefore necessarily accomplished primarily by bulk shortening of the basin fill.

Narrow, broadly east-west trending, linear zones of often intense folding occur in Mesozoic rocks at outcrop across southern England. South of the Chalk Downs one of the most northerly and important of these is the Hog’s Back Fault (also known as the Hog’s Back Monocline), at the boundary between the London–Brabant platform and the Weald Basin. To the north of this fold the beds form part of the southern limb of the London basin, while those to the south of it rise in a gentle curve, forming the northern margin of the ‘Wealden dome’ (Dines et al., 1929). It is responsible for the steep, northerly dip of the Chalk (up to 60°), producing the obvious pinch in the outcrop pattern seen between Farnham and Guildford, and the pronounced east–west orientated topographic ridge known as the ‘Hog’s Back’, which lends its name to the geological structure (Ellison et al., 2002). A complementary synclinal flexure is traceable to the south of the anticline and trends east-north-east through Bramley and the Blackheath area, beyond which it dies out. South of the Chalk Downs the main fold is an anticline, the axis of which passes through Clay Hill, Crooksbury Hill, Hampton Common, Compton, and Chantries, thus converging eastward towards the monoclinal fold of the Hog’s Back into which it merges at St Martha. The general dip of the south limb of the anticlinal fold in the west of the region averages from 2° to 3°; that of the north limb is of the same order, but it increases rapidly as it approaches the Hog’s Back fold (Dines et al., 1929).

The Pewsey–Southern London Platform Margin faults are thus important fault zones with variable net displacements and associated inversion-related folding; these faults transect the depth range of interest.

For more details see Howitt (1964); Chadwick et al. (1983); Chadwick (1986); Whittaker (1985); Lake and Karner (1987); Bristow et al. (1999) and Chadwick and Evans (2005).

5.3.2 Maidstone–Ashford fault zone

The Maidstone–Ashford fault zone is a north-west-trending, complex fault zone, downthrown to the south-west and extending over 38 km, mapped in Whittaker (1985). It has around 200 m normal displacement at top Variscan basement levels, which is in the 800 to 1100 m depth range, and marks the boundary between the Weald Basin and the stable, basement structural high of the London–Brabant massif (platform). The fault zone, inferred by Lake (1975), is the probable eastern extension of the Southern London Platform Margin Fault and is thought to extend offshore across the Channel into the Boulonnais region of northern France (e.g. Mansy et al., 2003).

For more details see Lake (1975); Barton et al. (2011); Bristow et al. (1991); Bristow (1995); Whittaker (1985); Chadwick (1986) and Mansy et al. (2003).

5.3.3 Penshurst–Tonbridge–Biddenden fault zone

The Penshurst–Tonbridge–Biddenden fault zone is a complex braided series of predominantly east–west-trending, Permian and Mesozoic syndepositional normal faults, downthrown to the south. Overall, the fault zone extends some 60 km from around Penshurst eastwards, south of Tonbridge, to Biddenden whereupon it swings to a more north-west trend, heading towards the coast around Lidd. It aligns roughly with the Dorking fold belt further west (which includes the Hog's Back structure).

Subsurface mapping shows the fault zone to be a complex of smaller *en échelon* faults with normal displacements of >200 m at top Variscan basement levels (e.g. Whittaker, 1985). The structure locally shows compressive characteristics, having experienced varying amounts of relatively minor reversal (Lake, 1975).

For more details see; Lake (1975); Barton et al. (2011); Bristow et al. (1991); Bristow (1995); Whittaker (1985) and Chadwick (1986).

5.3.4 Godley Bridge–South Groombridge/Finchcocks–Kilndown/Benenden fault zone

The Godley Bridge–South Groombridge/Finchcocks–Kilndown/Benenden fault zone is a complex, braided series of predominantly east–west-trending, *en échelon*, Mesozoic syndepositional normal faults, downthrown to the south. The fault zone extends east–west over 110 km. The structure locally shows compressive characteristics, having experienced varying amounts of relatively minor reversal, such that fault splays at surface have a net reverse displacement (downthrow to the north) e.g. the North Groombridge Fault.

The western segment, the Godley Bridge Fault, is around 40 km long with a displacement of up to about 300 m at top Variscan basement levels (Whittaker, 1985). The eastern segment, the South Groombridge/Finchcocks–Kilndown/Benenden Fault, is around 40 km in length with 315 m of normal displacement as measured from UK3D.

There are suggestions of strike-slip faulting, downthrow to the north displacements and anticlinal folding associated with the fault zone, supporting compressional phases. Many short periclinal folds occur in the Haslemere district, but the main folds associated with this fault zone are the Hindhead, Alford and Crowborough anticlines. The fault zone and folding may extend eastwards into the Winchester fault zone and associated folding, in the adjacent Hampshire region.

For more details see Thurrell et al. (1968); Bristow and Bazley (1972); Osborne White (1912); Lake (1975); Whittaker (1985); Chadwick (1986); Booth et al. (2008) and Farrant et al. (2011).

5.3.5 Brightling/Bolney–Mayfield fault zone

The Brightling/Bolney–Mayfield fault zone is a slightly arcuate, complex, predominantly east–west-trending, Permian and Mesozoic syndepositional normal fault zone, downthrown to the south. It extends over 60 km and has a displacement of about 265 m in UK3D. The structure locally shows compressive characteristics, having experienced varying amounts of relatively minor reversal, such that fault splays at surface have net reverse (downthrow to the north) displacements e.g. the Burnt Oak Fault. The Brightling No. 1 Borehole reveals several major reverse faults in the Lias sequence at about 1137.5 m, downthrowing about 180 m to the north and possibly linked to the Burwash Common Fault. Reverse faulting is also evident at the base of the Jurassic, where it rests upon Palaeozoic basement at 1322.2 m (Lake et al., 1987).

For more details see Lake (1975); Bristow and Bazley (1972); Lake et al. (1987); Whittaker (1985) and Chadwick (1986).

5.3.6 Buttons Farm–Burwash Common–Archerwood/Brede Valley fault zone

The Buttons Farm–Burwash Common–Archerwood/Brede Valley fault zone is an arcuate, sinuous, braided, predominantly east–west-trending, *en échelon*, Mesozoic syndepositional normal fault zone, downthrown to the south. Traced eastwards the fault zone curves south-eastwards, towards the coast in the area north of Eastbourne.

The western segment, the Buttons Farm–Burwash Common fault zone, extends approximately 25 km and has a displacement of about 500 m in UK3D. The eastern segment, the Archerwood/Brede Valley fault zone, extends about 20 km and has a displacement of about 200 m in UK3D.

For more details see Lake (1975); Whittaker (1985) and Chadwick (1986).

5.3.7 Sayers Common–Isfield–Horsebridge fault zone

The Sayers Common–Isfield–Horsebridge fault zone is an arcuate, sinuous predominantly east–west-trending, *en échelon*, Permian and Mesozoic syndepositional normal fault zone, downthrown to the south. It extends over 60 km and has a displacement of approximately 260 m in UK3D and is inferred at depth due to the presence of a series of anticlines recognised at crop, including the Singleton, Greenhurst and Pyecombe anticlines. The structure locally shows compressive characteristics, having experienced varying amounts of relatively minor reversal, such that faulting at surface has net reverse (downthrown to the north) displacements e.g. the Sayers Common Fault, with smaller splays having probable reverse movement. To the west, the Singleton anticline swings to a more east-north-east trend and to the north are complementary shallow synclinal structures, including the Henfield and Warminghurst synclines (Young and Lake, 1988).

For more details see Lake (1975); Lake et al. (1987); Young and Lake (1988) and Bristow and Bazley (1972).

5.3.8 Coghurst/Marsham fault zone

The Coghurst/Marsham fault zone is an arcuate, braided, mainly east trending, Permian and Mesozoic syndepositional normal fault zone, downthrown to the south. It extends over 17 km and has a displacement of about 225 m in UK3D. The fault zone is associated with the Fairlight Anticline, which itself shows intense strike and oblique faulting within its axial zone and high northerly dips (between the Coghurst and High Lankhurst faults). Other minor faults show reverse displacement at crop, including the Wilting and Haddock's faults and downthrown to the north Fairlight Cove reverse faults on the coast. Evidence thus supports the view that the fault zone shows compressive characteristics, having experienced varying degrees of relatively minor reversal arising from the rejuvenation of a major fracture in the Palaeozoic basement.

For more details see Lake (1975); Lake et al. (1987); Young and Lake (1988) and Bristow and Bazley (1972).

5.3.9 Saltdean–Willingdon fault zone

The Saltdean–Willingdon fault zone is a complex, predominantly east-trending Mesozoic syndepositional normal fault zone. It is poorly constrained, extending about 17 km onshore, with a downthrown to the south displacement of 915 m in UK3D and appears to have suffered some reversal during compressive phases, being closely associated with the Arlington–Kingston–Beddingham Anticline.

For more details see Lake (1975); Lake et al. (1987); Young and Lake (1988) and Bristow and Bazley (1972).

5.3.10 Eastbourne Fault

The Eastbourne Fault is a complex, predominantly east-trending, Permian and Mesozoic syndepositional normal fault zone, downthrown to the south. It extends approximately 20 km onshore and probably extends 30 km offshore to the east of Eastbourne.

For more details see Lake (1975); Lake et al. (1987) and Young and Lake (1988).

5.3.11 Portsdown/Middleton fault zone

The major Mere–Wardour–Portsdown fault zone is a complex, braided series of predominantly east-trending, arcuate, *en échelon*, syndepositional normal faults, downthrown to the south. It extends eastwards across the adjacent Hampshire Basin region and enters the south-western limits of the Wealden region to the north of Bognor Regis. The structures associated with the major fault zone are the more northerly Portsdown Ridge Fault, and approximately 5 km to the south, the Portsdown/Middleton fault zone. Together, they form the southern and south-western end of the main Weald Basin depocentre and south-eastwards extension of the Mere basin, and the northern margin of the Hampshire–Dieppe high. The faults, originating as downthrown to the south syndepositional normal faults in Permian times, and controlled by a major, southerly dipping Variscan basement thrust (the Wardour Thrust), show the greatest normal displacements at depth and suffered reactivation in extension on a number of occasions. They suffered varying degrees of reversal during the Cenozoic, with associated folding of the younger cover.

The south-dipping Portsdown Ridge Fault only just impinges on the south-western corner of the Wealden region. It has a length of approximately 51 km with a variable net displacement, having suffered significant reversal such that net reverse displacements are evident over a wide stratigraphical range along its length. To the south, the similarly south-dipping Portsdown/Middleton Fault has a length of about 80 km and a net displacement of 100 to 200 m. The fault zone extends further eastwards into the south of the Wealden region and is traced to the coast around Worthing, from where it continues about 15 km offshore into the English Channel. Changes in the thickness of the strata across the Portsdown–Middleton faults indicate major periods of active normal faulting during Early Jurassic and Late Jurassic times and during deposition of the Wealden 'Group' of the Early Cretaceous. However, the fault zone underlies the northern margin of the Portsdown and Littlehampton inversion anticlines and the net displacement reflects Cenozoic inversion.

For more details see Aldiss (2002); Hopson (1999); Chadwick and Evans (2005); Mortimore (2011) and Evans et al. (2011).

5.4 FOLDING

Folding of the younger cover seen in the region is of two distinct types, resulting from Cenozoic basin inversion episodes (e.g. Hamblin et al., 1992; Chadwick, 1993).

- **Regional upwarps** such as the Weald Anticline and Portland–Wight high in the adjoining Hampshire region to the west, which comprise major flexures with axial uplifts of more than 1000 m. These features appear to be associated with bulk shortening of the graben fill, and it is noteworthy that the greatest uplifts occur in basins that contain thick, Early Cretaceous sequences.
- **Long, roughly east-trending linear zones of *en échelon* inversion structures** are superimposed upon, and geographically delimit, the regional upwarps and coincide with the earlier graben-bounding faults affecting Variscan basement. They typically have the form of monoclinal or periclinal flexures each underlain by a partially reversed normal fault and, in many cases, often have high-angle reverse faults or thrusts developed in and the steepened limb.

For the purposes of this report, five major 'fold belts' are recognised associated with the fault zones listed below. Minor folds are found elsewhere but are of less significance.

- **Portsdown/Middleton fault zone** including the Portsdown and Littlehampton anticlines (Figure 15; Location 14.1)
- **Sayers Common–Isfield–Horsebridge fault zone and associated Singleton–Henfield–Hailsham–Eastbourne fold zone** includes the Pyecombe, Greenhurst and Singleton anticlines, the latter showing a more east-north-east to west-south-west trend and possibly linking to the Portsdown fault structures (Figure 15; Location 14.2)
- **Saltdean–Willingdon fault zone** including the Arlington–Kingston–Beddingham Anticline (Figure 15; Location 14.3)
- **Godley Bridge–South Groombridge fault zone** (Figure 15; Location 14.4)
- **Hog's Back–Southern London Platform Margin Fault** 'Dorking fold belt', including the Hog's Back Fault (Figure 15; Location 14.5)

5.5 UNCERTAINTY

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

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

The presence of faults, and their subsurface location, attitude and displacement, may be evidenced by geophysical techniques. These techniques themselves carry varying degrees of confidence, depending on their varying degrees of sensitivity and thus resolution. Potential field (gravity and aeromagnetic) data are the least sensitive techniques on which to base interpretations, with structures identified and mapped tending to be larger scale. Seismic reflection data, generally acquired during hydrocarbon and coal exploration, provide greater resolution and thus permit more accurate identification, location and mapping of fault(s) and other structures in the subsurface. Within the Wealden region, the distribution of seismic lines is relatively dense except in the north and east of the region (Figure 9). Where there is good coverage of seismic data, the recognition and location of subsurface faulting and folding carries higher confidence and is best constrained.

Seismic coverage is poor east of the M20 and north of the North Downs with only a few lines east of Canterbury, where only spatially restricted Coal Authority data are available. Principal uncertainties in seismic location depend on the spacing and quality of the seismic grid, migration (or not) of the data, and depth conversion of the interpretation. Experience shows that under good conditions, uncertainty of XY location should be better than 50 m; Z-depth uncertainty at 1000 m, about 50 m; and smallest recognisable vertical offset, about 20 m.

6 Screening topic 3: groundwater

6.1 OVERVIEW OF APPROACH

This section explains what is known of shallow and deep groundwater flow regimes in the Wealden 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) which 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 WEALDEN REGION

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

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The regional groundwater flow systems in the Weald 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 coastlines to the south and east of the region and the Thames catchment to the north of the region.

For the Wealden region, the GVS groups the rocks of the UK into three age ranges: the younger sedimentary cover sequence (Palaeogene to Permo-Triassic), older sedimentary rocks (Carboniferous) and basement rocks (Table 4, Column 1). The oldest rocks at outcrop in the Wealden region are within a string of narrow inliers of the Purbeck Group in central East Sussex, and slightly younger, within the Ashdown Formation of the Wealden Group, which crop out in the centre of the Weald Anticline. The youngest bedrock in the region is within small outliers of the Bagshot Formation (Bracklesham Group) on the Isle of Sheppey in north Kent, and the Palaeogene London Clay, which occurs only in small parts of the north-east and south-west of the region. The two main aquifers in the region, the Chalk Group (referred to herein 'the Chalk') and the Lower Greensand Group, both principal aquifers, are exposed around the margins of the Weald Anticline. The Chalk forms prominent areas of high ground dipping northward to form the North Downs, southward to form the South Downs, and at the western end of the Weald Anticline, the Chalk and Lower Greensand are exposed dipping broadly westward underneath the Hampshire Downs.

The units that act as regionally important sources of groundwater in the region are the Chalk Group (with the hydraulically connected Upper Greensand Formation) and the Lower Greensand Group. Most groundwater flow in the Chalk occurs through fractures at depths shallower than about 50 m below the lowest usual water level (Jones and Robins, 1999; Adams, 2008). There are separate active, relatively shallow groundwater flow systems in the North and South Downs. Groundwater tends to flow away from recharge areas, which are largely over the higher ground, towards discharge areas along the coast to the south and north-east, or northwards into the confined aquifers of the Thames basin. Groundwater in the Lower Greensand Group in the region generally flows radially outwards away from the central Weald Anticline, towards the north, north-west, west and south (Shand et al., 2003).

Below the Lower Greensand Group, only the Wealden Group and the Purbeck Group receive direct recharge. However, although there are units within these groups that are developed for local supplies of groundwater, they are not regionally significant and not designated as principal aquifers.

The underlying Jurassic to Triassic sediments that form the lower units in the younger sedimentary cover sequence of the GVS (Table 4) are not exposed in the region, do not receive direct recharge, and do not constitute regionally significant aquifers. They are typically found in or below the depth range of interest. There is no hydrogeological information on these units in this interval for the Weald region, although by analogy with neighbouring regions some limited observations regarding characteristic hydrogeological properties can be made.

The older sedimentary cover rocks and the basement rocks in the GVS (Table 4) are deeply buried, and typically found only towards the base of, or below, the depth range of interest. There is no hydrogeological information on these units in the literature reviewed for this region, although by analogy with other regions these units are expected to have low permeability.

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

- a relatively shallow groundwater system in the younger cover sequence consisting of the Chalk to Lower Greensand Group succession, with two distinct sub-regions associated with the North and South Downs, linked by the Hampshire Downs to the west of the region
- a groundwater system within the remaining exposed sedimentary cover rocks, i.e. the Early Cretaceous Wealden Group and Purbeck Group
- a groundwater system in the Jurassic to Triassic sedimentary sequence
- a relatively low-permeability system consisting of Devonian and early Palaeozoic basement rocks

There are a range of pathways for groundwater movement between some of these groundwater systems, and, in particular, within the shallower systems, principally associated with regional-scale structures and with anthropogenic features. These potential pathways for groundwater movement between units and groundwater systems are discussed after a description of each of the four groundwater systems.

6.3.1 Hydrogeology of the Chalk to Lower Greensand

The uppermost principal aquifer in the region, the Chalk, is overlain in some areas by younger sedimentary rocks, principally the Thames Group, the Lambeth Group and the Thanet Formation, which are everywhere shallower than the depth range of interest in the region. The Chalk is underlain by the Upper Greensand Formation with which it is typically in hydraulic continuity. The Gault underlies the Upper Greensand Formation and acts as a confining or leaky layer, providing hydraulic separation between the Upper Greensand Formation and the Lower Greensand Group (Forster et al., 1994).

6.3.1.1 THE CHALK GROUP

The Chalk is the most important principal aquifer in the Wealden region, occurring at outcrop in the North and South Downs (Jones and Robins, 1999; Adams, 2008). The Chalk in the North Downs dips gently towards the north and the Chalk in the South Downs dips gently towards the south (Allen et al., 1997). There is copious hydrogeological information for the Chalk of the North and South Downs. Most of this information relates to depths of not more than 200 m, although there is some limited information from buried Chalk to the north of the North Downs outcrop.

In this region, the Chalk Group comprises predominantly very fine-grained and pure homogeneous microporous limestone, with subordinate hardgrounds and beds of marl, calcarenite and flint (Adams, 2008). It is intersected by a complex system of fractures. The nature and extent of fracturing is controlled largely by the tectonic setting and structural history of the area (Jones and Robins, 1999), but it is also influenced significantly by lithology and diagenesis, particularly between Chalk with marls and without marl seams (Adams, 2008; Jones and Robins, 1999).

Groundwater flow in the saturated zone is predominantly through fractures and locally in solutionally enlarged conduits (Jones and Robins, 1999; Allen et al., 1997). Karst is present in some parts of the shallow Chalk aquifer (Allen et al., 1997), particularly along or close to the Palaeogene outcrop. Generally there is a non-linear decrease in transmissivity with depth, which is clearly seen during droughts when yields in major boreholes reduce dramatically for small falls in water table level (Allen et al., 1997). The non-linear decrease in transmissivity with depth is associated with significant vertical variations in fracture development in the Chalk, which reflect lithological variations. Many important groundwater flow horizons are concentrated in about a 50 m interval below the water table or below the top of the confined Chalk. At deeper levels, the frequency and aperture of fractures declines and is associated with a reduction in circulation of groundwater with depth (Jones and Robins, 1999), although smaller flows are locally present down to at least 140 m below the water table and are associated with marl layers, flints or hardgrounds (Allen et al., 1997; Jones and Robins, 1999; Adams , 2008). Fracture flow can be rapid. Flow velocities through larger fractures in the North Downs Chalk are of the order of tens to hundreds of metres per day (Adams, 2008). There is little information on the hydraulic characteristics of the Chalk in the depth range of interest in the region.

The dominant process affecting groundwater chemistry is the interaction between groundwater and the carbonate sediment of the Chalk matrix, which produces strongly pH-buffered groundwaters, with Ca and HCO_3 as the dominant ions in solution (Smedley et al., 2003), and groundwater that is almost always saturated with respect to calcite (Jones and Robins, 1999). Such groundwaters are particularly evident in the unconfined aquifer, where groundwater is typically oxidising (Smedley et al., 2003). Brackish waters have been seen at depths of 30 to 52 m near the coast in north Kent, with higher salinity water (4000 mg/l Cl) below 52 m (Edmunds and Milne, 2001). However, interstitial Chalk water from a deep inland borehole at Sompting near Worthing indicated that maximum salinity at the base of the Chalk at 325 m did not exceed 51 mg/l Cl (Edmunds and Milne, 2001). Groundwater in the Chalk Group in the region is mainly of Holocene age, and there is evidence for active and rapid recharge to the saturated zone (Edmunds et al., 1992). Groundwater abstraction has led to the intrusion of saline water up to 500 m inland in the South Downs Chalk, shown by hydrogeophysical logging to be flowing along discrete horizons (Edmunds et al., 2001).

6.3.1.2 UPPER GREENSAND FORMATION

The Upper Greensand Formation is present below the Lower Chalk and above the Gault Formation in the north and south of the region, but is absent in the north-east. It crops out on the escarpments of the North and South Downs. It is lithologically variable but generally comprises fine-grained, calcareous and glauconitic sands, which can be cemented to form a sandstone with a high proportion of colloidal silica, calcareous material and some clay and mica (Allen et al., 1997).

The Upper Greensand Formation is generally considered a poor aquifer, but where it underlies the Chalk Group it is usually thought to be in hydraulic continuity with the Chalk (Allen et al., 1997). Groundwater flow is both intergranular and through fractures, depending on the degree of cementation. This, and the degree of lithological variety, results in hydrogeological complexity (Allen et al., 1997). The Upper Greensand Formation generally has limited outcrop area and receives little direct recharge, but where it lies below the Chalk Group, much of its recharge is thought to derive from slow vertical leakage through the Lower Chalk (Allen et al., 1997). Where it is deeply confined by the Chalk Group, the Upper Greensand

Formation generally has relatively low permeability. There is no information about the hydrogeological properties of the formation in the depth range of interest in the literature reviewed.

6.3.1.3 GAULT FORMATION

The Gault Formation in the region forms a continuous outcrop around the central Weald area, and extends beneath the Chalk Group in the North and South Downs. It is dominated by soft mudstones and silty mudstones. The basal part can include sandy layers. There is no information about the hydrogeological properties of the formation in the depth range of interest in the literature reviewed.

The near-surface hydrogeology of the Gault Formation is strongly controlled by its level of disturbance and degree of weathering: the depth of weathering varies but rarely extends to 10 m (Forster et al., 1994). It is considered as a confining layer, an aquiclude usually or perhaps an aquitard because, like other clays and mudstones, there can be some groundwater leakage (Environment Agency, 2016). For example, Jones et al. (2000) states that some downward vertical groundwater flow occurs through the Gault Formation in the north-west of the Thames valley. Although this is outside this region, it indicates that groundwater flow through the Gault Formation can occur.

6.3.1.4 LOWER GREENSAND GROUP

The Lower Greensand Group is overlain by the Gault Formation, and underlain by the Weald Clay Formation, with sharp and unconformable boundaries (Allen et al., 1997). In the Wealden region it crops out around the edges of the Weald Anticline, but is not present in the centre of the region or below younger rocks in north-east Kent. The Lower Greensand Group is an important aquifer in south-east England. It is exploited around the margins of the Wealden region. It has a small outcrop area, but generally good water quality makes it a reliable source of groundwater (Allen et al., 1997). Lithologically, it comprises a complex series of clays and sands, of varying degrees of cementation.

In the depth interval of active groundwater exploitation the group does not behave as a single aquifer unit, but generally as two distinct aquifers: the Hythe Formation and the Folkestone Formation, which are separated by the lower permeability Sandgate Formation (Allen et al., 1997). The aquifer properties of the Hythe Formation are largely controlled by the degree of cementation of the sands and sandstones. In the north of the region there are two different lithologies: west of Redhill there are calcareous sands and sandstones, and east of Redhill there are limestones and sandy limestones (Allen et al., 1997). In well-consolidated sandstones, groundwater flow is primarily though fractures; in poorly cemented sandstones/sands, groundwater flow is generally intergranular (Allen et al., 1997). Permeability in fractured parts of the aquifer tends to be high, but unpredictable, while in parts dominated by intergranular flow, permeability tends to be moderate with little variation (Allen et al., 1997). The Folkestone Formation largely shows intergranular flow, but in some areas evidence for fracture flow exists (Allen et al., 1997). Hard ironstone layers within the formation have relatively low permeability and locally act as aquitards, stratifying groundwater flow within the aquifer. The Atherfield Clay forms a low permeability base to the Lower Greensand Group.

In the depth range of interest, as the aquifer becomes confined below the Gault Formation and thins, its transmissivity reduces significantly (Allen et al., 1997). An average permeability of 2.0×10^{12} m^2 has been estimated from a depth of 400 m in a borehole at Sompting (TQ 166 064). This is expected to reduce with increasing depth (Downing and Gray, 1986).

Groundwater in the Lower Greensand typically contains relatively low concentrations of carbonate minerals and is usually unsaturated with respect to calcite. Groundwater in parts of the confined aquifer can be reducing, leading to increases in some minor ions such as iron, and a component of saline water has been seen at depth (Morgan-Jones, 1985). The deep borehole at Sompting near Worthing (TQ 166 064) yielded fresh groundwater with a salinity of 100 mg/l from 404 to 457 m depth. The recharge area for the borehole is about 10 km to the north, from outcrop, and isotopic data indicates that despite its low mineralisation, the water is about 7880 years old or of early Holocene age (Edmunds and Milne., 2001).

6.3.2 Hydrogeology of the Wealden and the Purbeck groups

The Wealden Group and the Purbeck Group crop out in the centre of the Wealden Anticline and receive direct recharge. However, although there are units within these groups that are developed for local supplies of groundwater, they are not regionally significant and not designated as principal aquifers.

6.3.2.1 WEALDEN GROUP

The Wealden Group includes a variety of mudstone and sandstone units. Non-mudstone units of the Wealden Group include the Ashdown Formation and the Tunbridge Wells Sand Formation, both of which act as local sources of groundwater. Where it is not at outcrop (present at the ground surface or below Quaternary deposits), the Wealden Group is overlain by the Lower Greensand Group, which is a principal aquifer in the region. The Wadhurst Clay Formation generally acts as an aquitard, confining the underlying Ashdown Formation (Jones et al., 2000). There is limited information about the hydrogeological properties of the group in the interval of active groundwater exploitation, and no information in the depth range of interest in the literature reviewed.

Selley (2012) states that water boreholes drilled into the Weald Clay have long been notorious for emissions of ‘foul gas’, including a noteworthy gas discharge in a water borehole at Hawkhurst, 5 km east of Petworth in West Sussex. The Weald Clay is high in carbonaceous plant matter, sometimes sufficiently abundant as to form thin horizons of lignite. In view of the shallow depth of the gas it is almost certainly biogenic rather than thermogenic in origin (Selley, 2012).

The BGS Methane Baseline Survey study (Bell et al., 2016) provides summary data for methane concentrations in these formations across southern England, most of which are likely to have been sampled in the Wealden region. Methane concentrations are higher than those in the other aquifers in southern England, and the two highest values were from the same borehole in the Tunbridge Wells Sand in the Weald Basin (Bell et al., 2016). The source of methane in this borehole was not definitively identified, but could be either thermogenic gas that migrated up from depth, or of biogenic origin, sourced from thin lignite layers in the Weald Clay (Bell et al., 2016). Bell et al., (2016) states that there is a known zone of shallow methane in the Wealden region, with hydrocarbon well logs from the area reporting significant gas in shallow Cretaceous sandstones.

6.3.2.2 PURBECK GROUP

The Purbeck Group comprise thick beds of gypsum-anhydrite, with limestones and mudstones, overlain by a main sequence dominated by mudstones, sometimes with thin limestone beds and rare thin sandstone beds. There is no systematic information about the hydrogeological properties of the group in the interval of active groundwater exploitation, and no information in the depth range of interest in the literature reviewed. Jones et al. (2000) state that limestones within the Purbeck Group of the Weald contain water in fractures. The fractured limestones are of limited importance for supply, as their outcrop is not extensive, but groundwater flows from them into gypsum mines. The water is very hard, due to its contact with the limestone and gypsum.

6.3.3 Hydrogeology of the Jurassic to Carboniferous cover

The Jurassic to Carboniferous sedimentary cover sequence is not exposed within the region and i typically found in or below the depth range of interest. There is no hydrogeological information on these units in this interval for the Wealden region, although by analogy with neighbouring regions some limited observations regarding characteristic hydrogeological properties can be made.

6.3.3.1 JURASSIC SEDIMENTS

The Portland Group has variable lithology, from dominated by mudstones, silty mudstones and muddy siltstones with thin sandstone beds, to dominated by both calcareous sandstones and sandy mudstone, and in some areas including muddy limestones. The upper part of the group comprises the Portland Stone Formation; the lower part comprises the Portland Sand Formation. There is no systematic information about the hydrogeological properties of the group in the interval of active groundwater exploitation, and no information in the depth range of interest in the literature reviewed. The Portland Stone Formation is considered to be a principal aquifer in the Wealden region, although in this region the formation is represented by calcareous and glauconitic sandstones, unlike in the type area for the Portland Group in Dorset (Gallois, 1965). There are few available aquifer properties data for the Portland Stone Formation anywhere across its occurrence in southern England, and none have been seen for the Wealden region in the literature consulted.

The Kimmeridge Clay Formation comprises fine-grained sandstones and siltstones, passing upwards into mudstones, which dominate the formation over most of the region. The sequence becomes sandier northwards and eastwards, with some limestones particularly in Kent. Little information is available on the hydrogeology of the Kimmeridge Clay Formation in the Wealden region: there is no systematic information about the hydrogeological properties of the group in the interval of active groundwater exploitation, and no information in the depth range of interest in the reviewed literature. Selected information from elsewhere is presented here to illustrate the possible hydraulic characteristics of the formation in this region. Jones et al. (2000) states that some downward vertical groundwater flow occurs through the Kimmeridge Clay in the north-west of the Thames valley, and that in the Ock valley west of Abingdon, some groundwater discharge occurs through the Kimmeridge Clay. Although outside this region, it indicates that groundwater flow through the Kimmeridge Clay Formation can occur. Selley (2012) states that a hydrocarbon borehole near Netherfield in West Sussex, in this region, drilled to around 580 m depth through the Kimmeridge Clay produced cores that showed that the Kimmeridge Clay was extensively fractured: some fractures were cemented with calcite and others were open and saturated with oil.

The Corallian Group has variable lithology, comprising limestones, sandstones, siltstones and mudstones, sometimes silty and/or calcareous. Little information is available on the hydrogeology of the Corallian Group in the Wealden region: there is no systematic information about the hydrogeological properties of the group in the interval of active groundwater exploitation, and no information in the depth range of interest in the reviewed literature. Selected information from elsewhere is presented here to illustrate the possible hydraulic characteristics of the group in this region.

In the Wessex Basin in the neighbouring Hampshire region to the west where it is at outcrop, the Corallian Group forms a multilayered aquifer with thin permeable limestone and sandstone horizons separated by confining layers, and artesian conditions are common (Jones et al., 2000), and in parts of Oxfordshire in the Abingdon area (Thames region), where the formation becomes confined below overlying units, artesian conditions can occur.

The Oxford Clay Formation comprises mainly mudstones, with some carbonaceous/bituminous or calcareous silty intervals, which can form hard ‘cementstone’ beds. There is no systematic information about the hydrogeological properties for these formations in the interval of active groundwater exploitation, and no information in the depth range of interest in the reviewed literature. Jones et al. (2000) state that some upward vertical groundwater flow occurs through the Oxford Clay in the north-west of the Thames valley. Although outside this region, it indicates that groundwater flow through the Oxford Clay Formation can occur.

The Great Oolite Group lies below the Kellaways Formation and Oxford Clay Formation, and above the Inferior Oolite Group. In the neighbouring Hampshire Basin region the Great Oolite Group is largely mudstone, but contains some limestones. The Inferior Oolite Group consists of varied bioclastic, peloidal, sandy, ferruginous, argillaceous, bioturbated limestones with subordinate ooidal limestone, sandstone, limestone conglomerate, lime-mudstone and mudstone beds; it is typically thin and rubbly, and bedded with many well-developed hard grounds.

The Great Oolite and Inferior Oolite groups are not significant aquifers in the Wealden region – it is likely that both are greater than 400 m deep across the whole region – and neither are used for water supply in the region. There is no systematic information about the hydrogeological properties for these formations in the depth range of interest in the reviewed literature.

The Lias Group is formed of calcareous, locally ferruginous or bituminous mudstones and shales. The Blue Lias Formation in the lower Lias Group is typically considered to act as an aquifer where it is present at outcrop or shallow depths (<200 m) in other regions. However, there is no information about the hydrogeological properties of this formation in the depth range of interest in the reviewed literature for the Wealden region.

The Mercia Mudstone and Sherwood Sandstone groups occur at depth across the region, though rarely present above a depth of 1000 m. The Mercia Mudstone Group comprises largely of mudstones, usually silty and locally calcareous, and commonly containing gypsum and anhydrite, with minor local sandstones, breccias and conglomerates. The Sherwood Sandstone Group consists of sandstones, mudstones, marls and breccias. There is no information about the hydrogeological properties of these groups in the depth range of interest in the reviewed literature for the Weald region.

The Warwickshire Group is thought to occur only in the extreme north-east of the region, within the area of the Kent coalfield, where it comprises of sandstones with some sandy shales and coal seams.

The Carboniferous Limestone Supergroup has two distinct divisions in the region: a lower limestone shale, consisting of dark shales with thin limestone bands, and an upper main limestone division, which consists of massive and crystalline limestones, although marl and oolite partings occur (Gallois, 1965). The Environment Agency aquifer designation classifies it as a principal aquifer in the Peak District (Derbyshire), the Mendip Hills, South Wales, North Wales and north-east England, but the Carboniferous Limestone Supergroup is not considered a major aquifer in the Wealden region (Allen et al., 1997).

6.3.4 Hydrogeology of the basement rocks

Devonian and early Palaeozoic rocks are present in the depth range of interest only in the east of the region; in other areas they are deeper than 1000 m. Very little information on these rocks in the Wealden region is available from either boreholes or seismic surveys and there is no information about their hydrogeological properties in the reviewed literature for the region.

6.4 EVIDENCE FOR CONNECTION AND SEPERATION BETWEEN GROUNDWATER SYSTEMS

6.4.1 Separation of aquifers

There are a number of rock units in the depth range of interest that are known or inferred to have low permeability, and which could therefore restrict vertical and horizontal movement of groundwater and contribute to hydraulic separation, such as the Gault Formation, Weald Clay Formation, Oxford Clay Formation, Lias Group and Mercia Mudstone Group. However, these units are not laterally continuous across the whole region: they are discontinuous due to lateral and vertical lithological changes, and to the movement of rock units along faults. In addition, although dominated by low permeability lithologies such as shales, mudstones and clays, they also include numerous thin beds and lenses of sandstone and siltstone, pebble beds and limestones, which are likely to have higher permeability. Consequently, the potential of any of these units to separate regional groundwater systems is limited and will vary across the region.

6.4.2 Connection of aquifers

6.4.2.1 GEOLOGICAL PATHWAYS

There is no evidence for thermal springs (>15º C) in the region based on the literature sources consulted. A groundwater abstraction from the Lower Greensand Formation at depths of between around 400 m and 450 m in a borehole at Sompting (TQ 166 064) was recorded at 21°C. No other evidence of groundwater temperatures at depths of more than 200 m has been seen in the literature sources consulted.

A detailed description of the geological structure of the region, including faulting, is given in Evans (2016). In particular, there is extensive faulting in the central part of the region. Some of the faults extend from depth to surface, offsetting strata of all ages from Devonian to the Cretaceous Chalk; others do not extend upwards into the Chalk but offset all older strata. Little detailed information on faulting and any hydrogeological effects is available at depths of more than 200 m. However, at depths of less than 200 m the impacts of faulting are seen extensively in the Wealden Group. The effects of faulting are seen less in the Weald Clay, except in the immediate vicinity of junctions with the Lower Greensand (Gallois 1965), but this may be a consequence of the difficulty of mapping faults, especially in the south and east of England (Aldiss, 2013), rather than a real effect.

The extensive faulting in the Wealden Group is known to cause large variations in groundwater levels in the Ashdown and Tunbridge Wells Sand formations (Jones et al., 2000). Where faults inhibit groundwater flow, different rest water levels are seen in boreholes either side of faults, e.g. in boreholes at Chase Wood (TQ 5929 3659) (Jones et al. 2000). Jones et al. (2000) also state that there is evidence suggesting that recharge to the lower Ashdown Formation may occur via fault-generated conduits through the Wadhurst Clay Formation, indicating that some faults form permeable conduits and allow groundwater flow. Faulting continues throughout the whole of the Wealden Group, and so it is possible that faults may form permeable pathways for groundwater throughout the group.

6.4.2.2 ANTHROPOGENIC PATHWAYS

Most boreholes into the depth range of interest are in the north, central or western parts of the region, and are focused on oil or gas resources, or in east Kent into the coalfield concealed below the North Downs. Currently only one well actively produces gas, at Albury near Guildford, and there are seven oil wells in the region. There are some water abstractions taking place from deep, confined Lower Greensand sources, including for example a site near Northfleet where abstraction is taking place from a borehole of >250 m depth (Environment Agency, 2016). Information on mining and other anthropogenic resource development in the region, including a map of 'intensely drilled areas', are provided in Section 8.

Most of the boreholes, with the exception of hydrocarbon producing wells, are likely to be now disused. No evidence for vertical flows between rock units in deep boreholes has been found in the references consulted, but if the boreholes were not fully sealed when decommissioned, they could form pathways for vertical flows between permeable units, which would otherwise be hydraulically separated by intervening low permeability units.

Anthropogenic influence on the Chalk

At shallow depths above the depth range of interest, some parts of the Chalk in the region have horizontal adits constructed from wells for up to at least 4 miles (approximately 6.5km) (Gallois, 1965). Tunnels and adits are common in the Isle of Thanet and elsewhere in east Kent, as are shallow chalk workings and shafts, and are likely to significantly modify aquifer properties (Allen et al., 1997).

An example of mining-related impacts on Chalk groundwater was the extensive discharge of minewater from the Tilmanstone colliery into unlined pits in unconfined Chalk at the ground surface, which resulted in an area of about 30 km^2 of the Chalk aquifer becoming contaminated with saline water, with Cl concentrations up to 5000 mg/l, in a pollution plume estimated to be about 100 m thick (Bird et al., 1999; Oteri, 1981).

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

It is clear from the recent geological record that glaciers have been repeatedly active within the UK landscape over the past two and half million years (Clark et al., 2004; Lee et al., 2011). Numerous periods of glaciation have been recognised, although the scale and extent of glaciers have varied considerably. Most glaciations have been comparatively small (i.e. highland glaciations), although some have been more extensive with glaciers expanding into lowland parts of the UK, i.e. lowland glaciations (Clark et al., 2004; Lee et al., 2011). Over the past half a million years, at least two continental-scale glaciations have affected the UK with ice sheets covering parts of lowland UK, on one occasion as far south as the London area (Figure 16; RWM, 2016b; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next one million years is open to conjecture (Loutre and Berger, 2000). This is because the impacts of global warming and the current melting of the Greenland Ice Sheet on the long-term climate system are poorly understood, although the general scientific consensus is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions means that their occurrence cannot be discounted.

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

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

7.2.2 A regional perspective

It is widely accepted that the Wealden region is situated beyond the limits of continental and lowland scale glaciation during the last two and half million years (Quaternary Period; see Figure 16: Shaw et al., 2012, Clark et al., 2004). Based upon the absence of evidence for past glaciations of this scale in the recent geological past, it is unlikely that the region will experience glaciation over the next million years except under exceptional circumstances (RWM, 2016b). However, the region may be affected by isostatic rebound or a glacier forebulge relating to the glaciation of an adjacent onshore area (e.g. Wealden: RWM, 2016b). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (RWM, 2016b). The extensive coastline of the Wealden region makes coastal areas of the region susceptible to saline groundwater incursion due either to global sea-level change (driven by global patterns of glaciation) or regional isostasy (RWM, 2016b). Saline groundwater incursion may alter the temporal and spatial patterns of groundwater behaviour (RWM, 2016b).

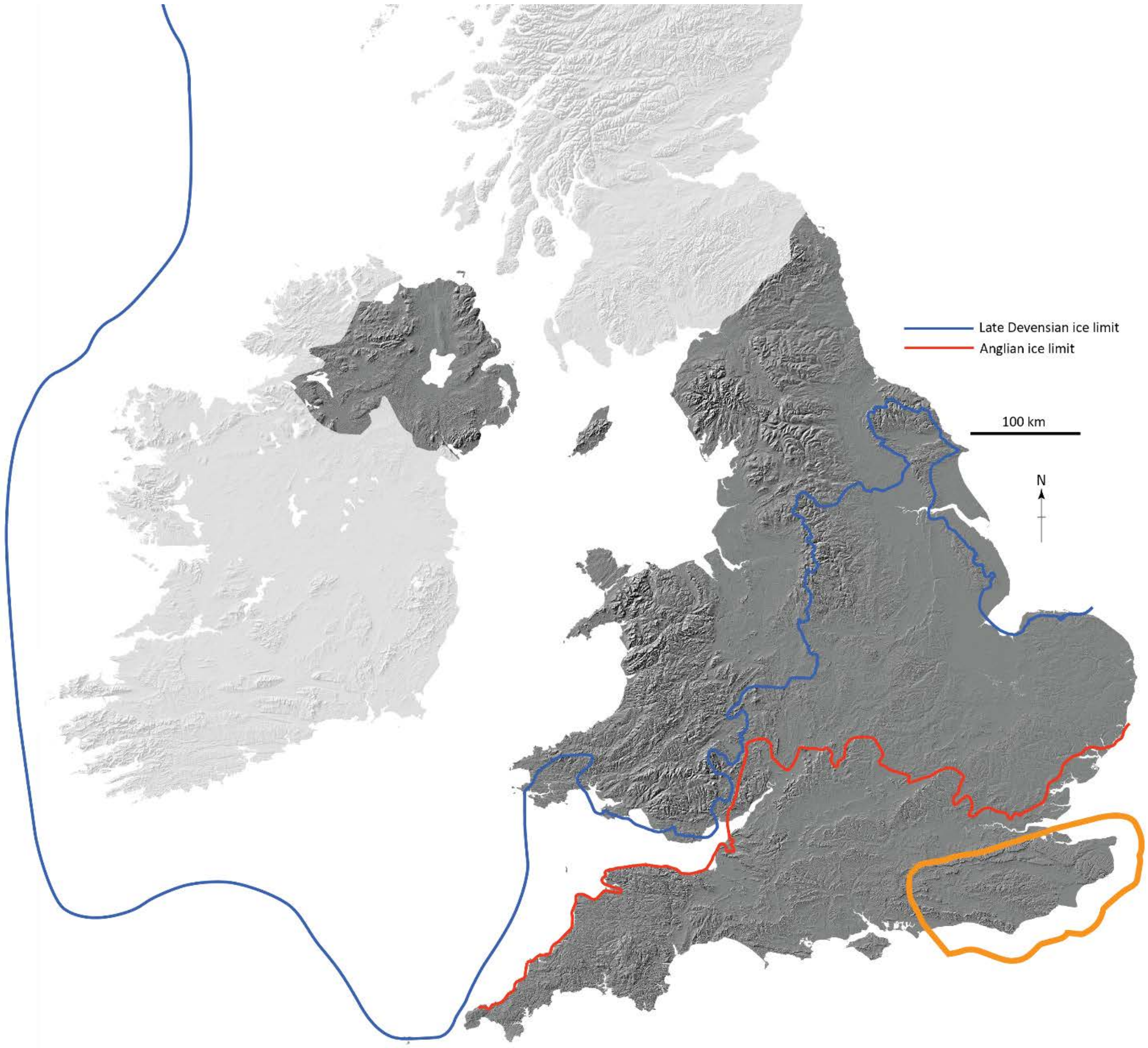


Figure 16 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and late Devensian (around 30 to16 ka). The location of the Wealden region is delineated by the orange line. Produced using Copernicus data and information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

7.3 PERMAFROST

7.3.1 A UK-scale context

Permafrost (frozen ground) occurs when the temperature of the ground remains below 0°C for at least two consecutive years (French, 2007). Permafrost, therefore, develops where average air temperatures are much colder than in the UK at 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 16) have all been affected by permafrost as indicated by the extensive weathering of surface geological materials (Shaw et al., 2012). Permafrost is important because its presence can affect the subsurface within the depth range of interest by altering groundwater behaviour and chemistry. This is especially the case if the current ground surface has been lowered by glacial erosion (Shaw et al., 2012).

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

7.3.2 A regional perspective

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

7.4 SEISMICITY

7.4.1 A UK-scale context

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

Earthquake activity is greatest at the boundaries between the Earth's tectonic plates, where the differential movement of the plates results in repeated accumulation and release of strain (Figure 17). However, earthquakes can also occur within the plates far from the plate boundaries, and where strain rates are low. Such earthquakes are commonly referred to as 'intraplate earthquakes'.

The UK lies on the north-west part of the Eurasian plate and at the north-east margin of the North Atlantic Ocean (Figure 17). The nearest plate boundary lies approximately 1500 km to the north-west where the formation of new oceanic crust at the Mid Atlantic Ridge has resulted in a divergent plate boundary associated with significant earthquake activity. Around 2000 km south, the collision between Africa and Eurasia has resulted in a diffuse plate boundary with intense earthquake activity throughout Greece, Italy and, to a lesser extent, North Africa. This activity extends north through Italy and Greece and into the Alps. The deformation arising from the collision between the African and European plates results in compression that is generally in a north–south direction. The north-east margin of the North Atlantic Ocean is passive (i.e. transition between oceanic and continental crust) and is characterised by unusually low levels of seismic activity in comparison to other passive margins around the world (e.g. Stein et al., 1989). As a result of this geographical position, the UK is characterised by low levels of earthquake activity and correspondingly low seismic hazard.

The continental crust of the UK has a complex tectonic history formed over a long period of time. It has produced much lateral and vertical heterogeneity through multiple episodes of deformation, e.g. on the Highland Boundary Fault (Woodcock and Strachan, 2000), resulting in widespread faulting. Some of the principal fault structures represent major heterogeneities in the structure of the crust and have been the focus of later deformation. Earthquake activity in the UK is generally understood to result from the reactivation of these existing fault systems by present day deformation, although such faults need to be favourably orientated with respect to the present day deformation field in order to be reactivated (Baptie, 2010).

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

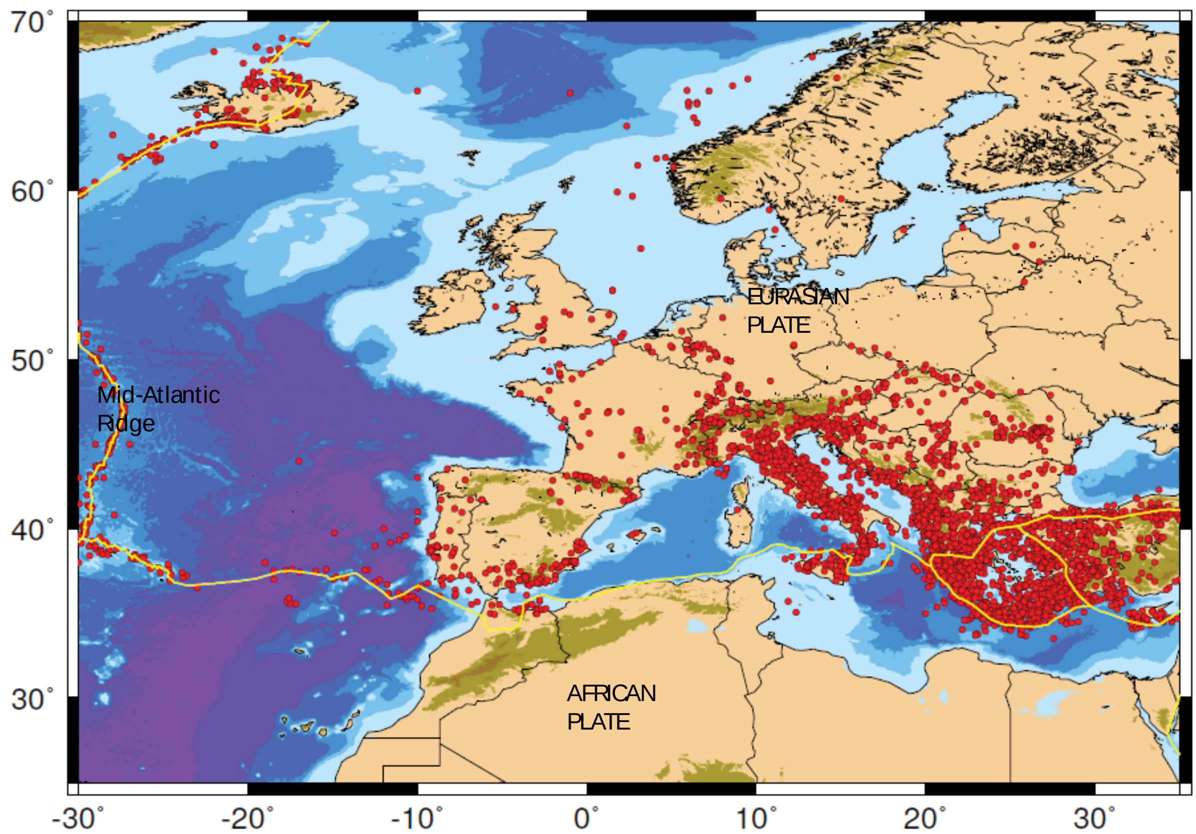


Figure 17 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated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

7.4.2 Seismicity catalogue

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

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

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

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

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

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

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

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

A requirement for any statistical analysis of seismicity is that one needs to know the extent to which the record of main shocks in an earthquake catalogue is complete. For example, some historic earthquakes that happened may not be present in the catalogue because no record of them survives to the present day. Normally, completeness improves with time (better nearer the present day) and also with magnitude (better for larger earthquakes). Thus one can describe a series of time intervals within which it is considered that the catalogue definitely contains all earthquakes above a certain magnitude threshold. This threshold value can be defined as the lowest magnitude at which 100 per cent of the earthquakes in a space-time volume are detected (Rydelek and Sacks, 1989). Therefore it is usually low for recent seismicity and gets progressively higher back in time. For this study we use the completeness estimates for the UK catalogue determined by Musson and Sargeant (2007), which are shown in Table 5. The catalogue for earthquakes of Mw 3 and above is complete from 1970, i.e. the beginning of the instrumental monitoring of the British earthquakes. The catalogue is complete for earthquakes above Mw 4 and Mw 5 from 1750 and 1650, respectively. In south-east England, the catalogue extends further back in time (to the 14th century) for earthquakes of Mw 5.5 and above.

Table 5 Completeness values for the BGS seismicity catalogue (after Musson and Sargeant, 2007).

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

Figure 18 shows a map of all of the main shocks in the catalogue. The symbols are scaled by magnitude (Mw). It is worth noting that the location uncertainty is ±5 km for instrumental earthquakes and up to ±30 km for historical earthquakes (Musson, 1994). An analysis of the British seismicity clearly shows that it is not correlated with the major tectonic structures that bound the tectonic terranes in the UK (Musson, 2007). The terranes are homogeneous in terms of crustal properties (e.g. distribution and style of faulting), but the seismicity within each block is heterogeneous (Musson, 2007). There are spatial variations in the level of seismic activity across the UK. Western Scotland, western England, Wales, south-western Cornwall and the area off the coast of the south-eastern England are the areas of highest activity. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free.

It is generally observed that the geographical distribution of British seismicity of the modern instrumental period follows rather closely the same distribution as the historical record of the last 300 years. However, there are three significant exceptions to this: south-west Wales, the Dover Straits, and Inverness. In these areas there was an intense historical seismic activity (as shown by the squares in Figure 18), which does not correspond to an intense instrumental seismicity. The Dover Straits area is notable for having produced relatively major (≥5 Mw) earthquakes in historical times (the last in 1580) and very little since.

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

7.4.3 Earthquake depths

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

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

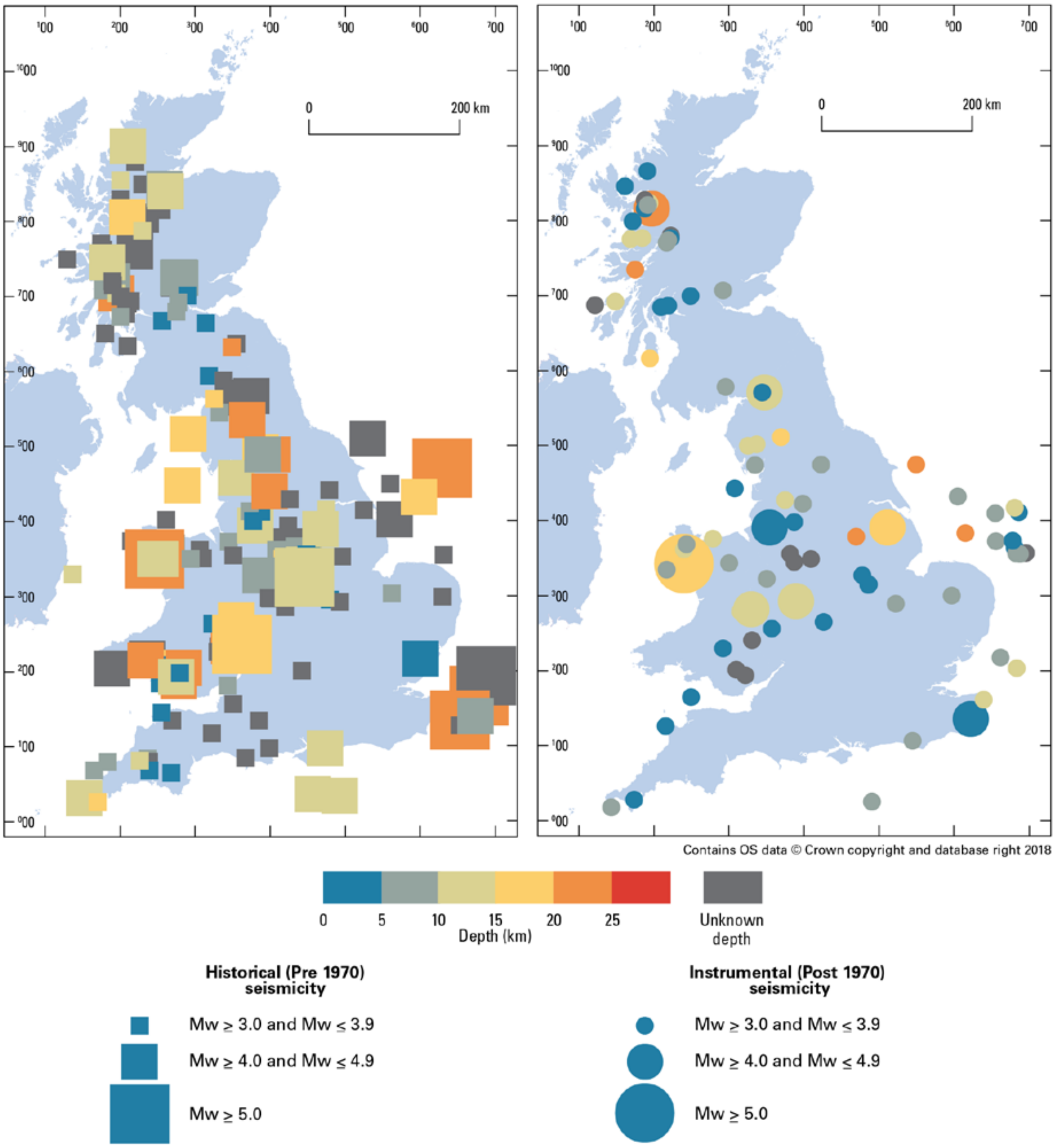


Figure 18 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological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

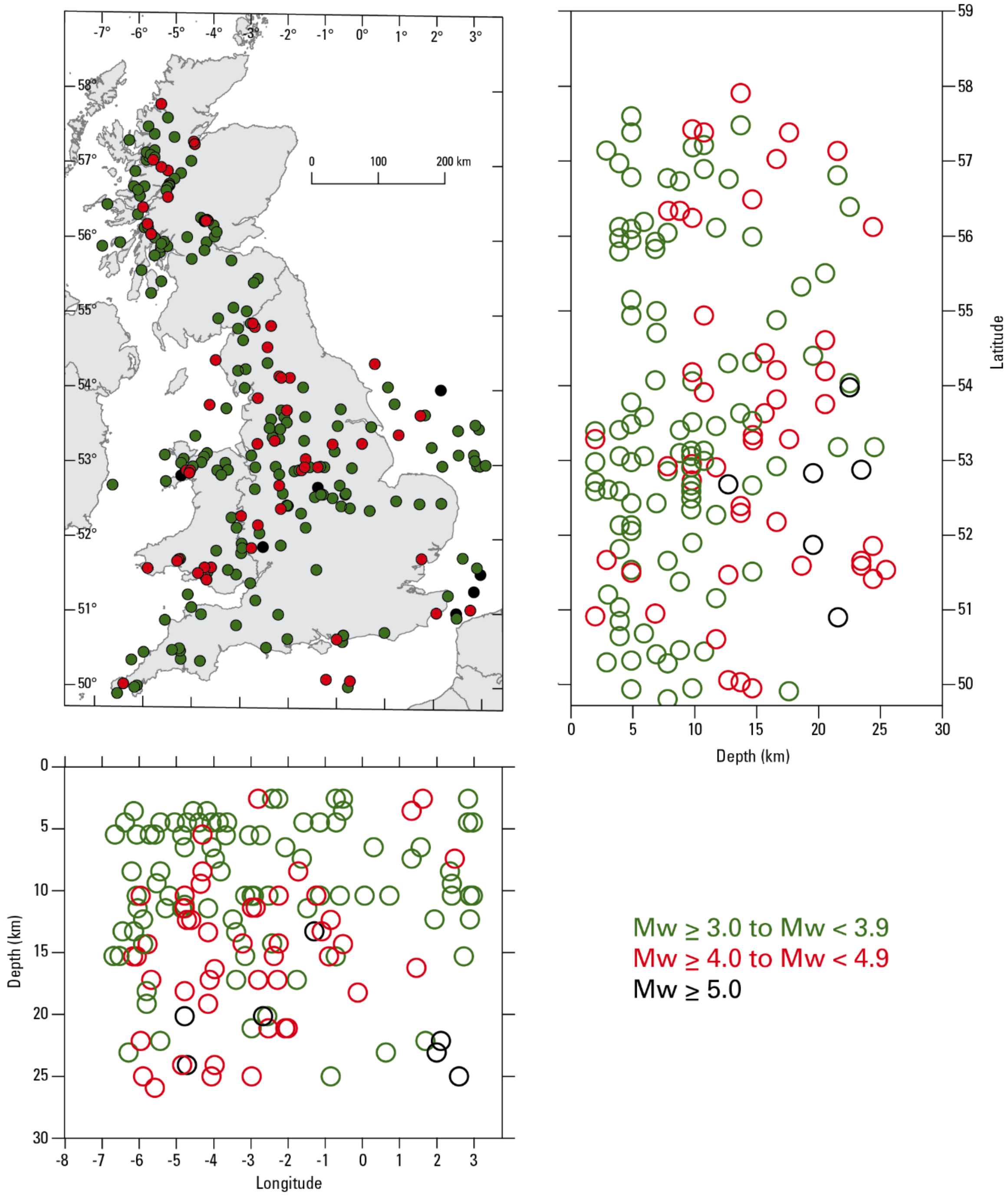


Figure 19 Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free.

7.4.4 Maximum magnitude

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

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

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

7.4.5 Earthquake activity rates

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

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

where N is the number of earthquakes per year greater than magnitude M and a is the activity rate, a measure of the absolute levels of seismic activity. The b-value indicates the proportion of large events to small ones. Determining these parameters is not straightforward due to the limited time window of the earthquake catalogue and the trade-off between the two parameters. Furthermore, when the number of events is small, the uncertainty in the b-value is high. For this reason, it is desirable to be able to maximise the amount of data available for the analysis. The maximum likelihood procedure of Johnston et al. (1994) is one approach. This method is able to take into account the variation of catalogue completeness with time (Table 4) and computes a 5 x 5 matrix of possible values of a and b along with associated uncertainties while also taking into account the correlation between them.

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

7.4.6 Impact of future glaciation

The possibility of renewed glaciation in the next ten thousand years means that estimates of the distribution and rates of regional seismicity cannot be considered the same as they are now. Geological investigations in a number of regions have found evidence for significant postglacial movement of large neotectonic fault systems, which were likely to have produced large earthquakes around the end-glacial period. For example, Lagerbäck (1979) suggests that the 150 km long, 13 m high fault scarp of the Pårve Fault in Sweden was caused by a series of postglacial earthquakes. Adams (1996) finds evidence for postglacial thrust faults in eastern Canada. Davenport et al. (1989) and Ringrose et al. (1991) find similar evidence for significant postglacial fault displacements in Scotland. However, Firth and Stewart (2000) 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

Although south-east England shows low levels of seismicity onshore, there have been at least three earthquakes with magnitudes of 5 Mw or greater in the Dover Straits in last 1000 years (Figure 20). Historical data sources suggest that they resulted in damage across parts of south-eastern England and as far north as London (Musson, 1994). The magnitude 5.5 Mw earthquake in 1382 is well-documented in both south-east England and mainland Europe, with accounts of damage in Canterbury and Hollingbourne. A magnitude 5.5 Mw earthquake in 1580 had an epicentre between Dover and Calais and was felt over most of England as well as much of northern France, Belgium and the Netherlands. Damage was caused in Kent and the Pas de Calais area, as well as in London, where the deaths of two people have been linked to this earthquake. A magnitude 5.0 Mw earthquake in 1449 was also felt in south-east England, but thought to be in the Dover Straits (Musson, 1994).

More recently a magnitude 4 Mw earthquake occurred near Folkestone on 28 April 2007 (Ottemöller et al., 2009). This resulted in emergency measures being taken by the local authority, power outages, transport disruptions and superficial damage to buildings (Baptie, 2008). The combination of a shallow focus and strong site amplification resulted in localised damage of a severity not seen in the UK in at least fifty years (Musson and Walker, 2007).

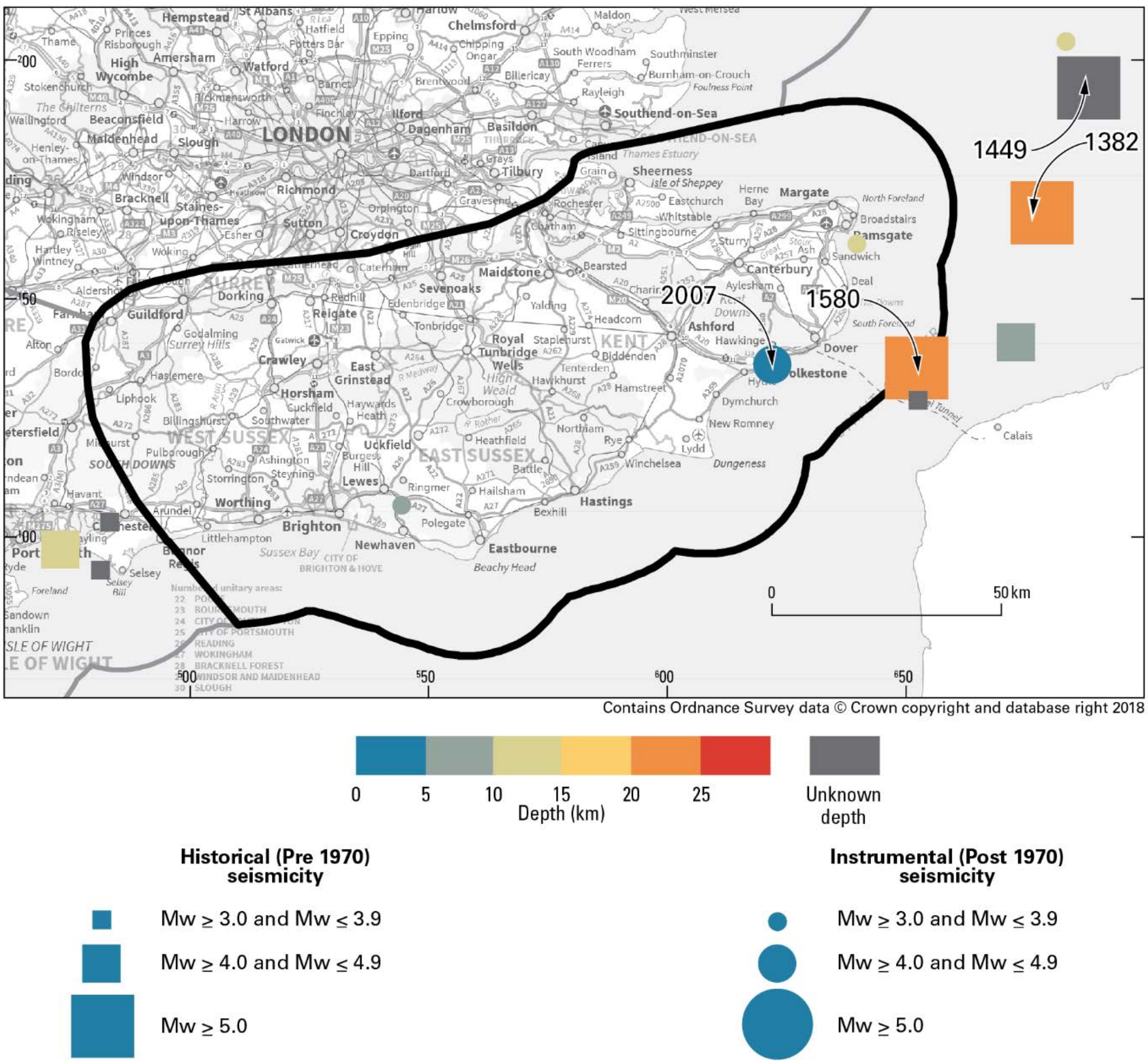


Figure 20 Historical and instrumentally recorded earthquakes in the Wealden region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI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

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

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

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

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

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

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

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

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

8.2 OVERVIEW OF REGION

Mineral resources in the Wealden region are shown on Figure 21. The Wealden region is a small conventional oil and gas producing region. A large part of the region is underlain by deep mudstones that are prospective for shale oil. Coal has previously been mined in east Kent and gypsum is currently mined in East Sussex. Historically the Weald was a major iron producing area, but the ores were mined at shallow depths only. There is known past shallow mining for sand, building stone, chalk and limestone in several areas of the Weald. There are clusters of deep (greater than 200 m below NGS datum) boreholes in the region related to the assessment of mineral and hydrocarbon resources.

8.3 COAL AND RELATED COMMODITIES

Coal has been mined from the Coal Measures at depths greater than 100 m below NGS datum in east Kent. East of Folkestone and Canterbury parts of the coalfield have not been exploited with coal seams remaining in situ above 500 m depth. The Kent coalfield is the most southerly coalfield in England and extends eastwards under the English Channel. Coal is concealed entirely beneath a cover of Mesozoic and Palaeogene rocks at depths between 300 and 1500 m (Figure 23). All working in this coalfield has now ceased, although coal was mined from collieries at Tilmanstone (closed 1986), Betteshanger (closed 1989), Snowdon (closed 1988), Chislet (closed 1969) and Shakespeare Cliff (closed 1915).

There are no current licences for coalbed methane, coal mine methane, abandoned mine methane or coal gasification. The Kent coalfield shows generally very low methane yields, which is unusual in high rank coals.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

Gypsum is mined at depths greater than 100 m below NGS datum in the Brightling and Robertsbridge areas of east Sussex. Until 1990, gypsum was worked underground from mines at Mountfield and Brightling. Following closure of the Mountfield mine in 1998, production is centred at Brightling. This mine is the only operating deep mine in south-east England. Natural gypsum and anhydrite occur as beds or nodular masses up to a few metres thick. The gypsum seams are on average 4 to 5 m in thickness and are extracted using the room and pillar mining method. The maximum depth of working is around 300 m below NGS datum.

Gypsum resources extend beneath overlying Cretaceous cover and are found within a series of small ‘inliers’ of Jurassic age rocks. Trial boreholes have confirmed the presence of basal Purbeck evaporites at depth around the inliers and elsewhere in the region. In general, at depths greater than 150 m, anhydrite rather than gypsum is present.

8.5 OTHER BEDDED AND MISCELLANEOUS COMMODITIES

There are no deposits of bedded or other miscellaneous deposits that have been worked deeper than 100 m below NGS datum in the region. However, the Weald is an ancient area of iron exploitation, annotated on Figure 21, and iron ores were extracted from shallow workings into the 19th century. There is known past shallow mining for sand, building stone and limestone in several areas of the Weald.

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 several onshore hydrocarbon fields in the region all along the northern edge between Sevenoaks and Guildford and in the south-west corner (Figure 21). There are eight gas fields in the north and centre of the region and seven oilfields. Currently only one well actively produces gas, at Albury near Guildford, and all seven oil wells are producing.

A large area in the Weald contains mudstones that have been identified as having potential for shale oil. However as yet there has been no drilling and testing to prove any resources. The Horse Hill discovery of oil from limestones in Kimmeridgian rocks probably means that it a hybrid oil shale/conventional reservoir.

8.8 GAS STORAGE

Depleted hydrocarbon fields have been considered for underground gas storage on the western limits of the region, but so far none have progressed to the planning application stage or been converted.

8.9 GEOTHERMAL ENERGY

There are no deep geothermal heating systems currently operating in the Weald. Regionally there is little geothermal energy potential in the Weald because of a lack of large granite intrusions or deep porous sedimentary basins. Very locally in east Kent there is the potential for minor district heating schemes using ground sourced heat pumps in abandoned mine workings of the Kent coalfield. However, as yet, there has been no scheme implemented.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are clusters of deep (greater than 200 m below NGS datum) boreholes in the region (see Figure 22). These are related to the assessment of the coal resources in east Kent, the gypsum deposits around Brightling and Robertsbridge and for hydrocarbon exploration and exploitation. There is also a cluster of deep boreholes around Rochester and the Medway estuary related to the construction of port infrastructure and oil and gas facilities in this area.

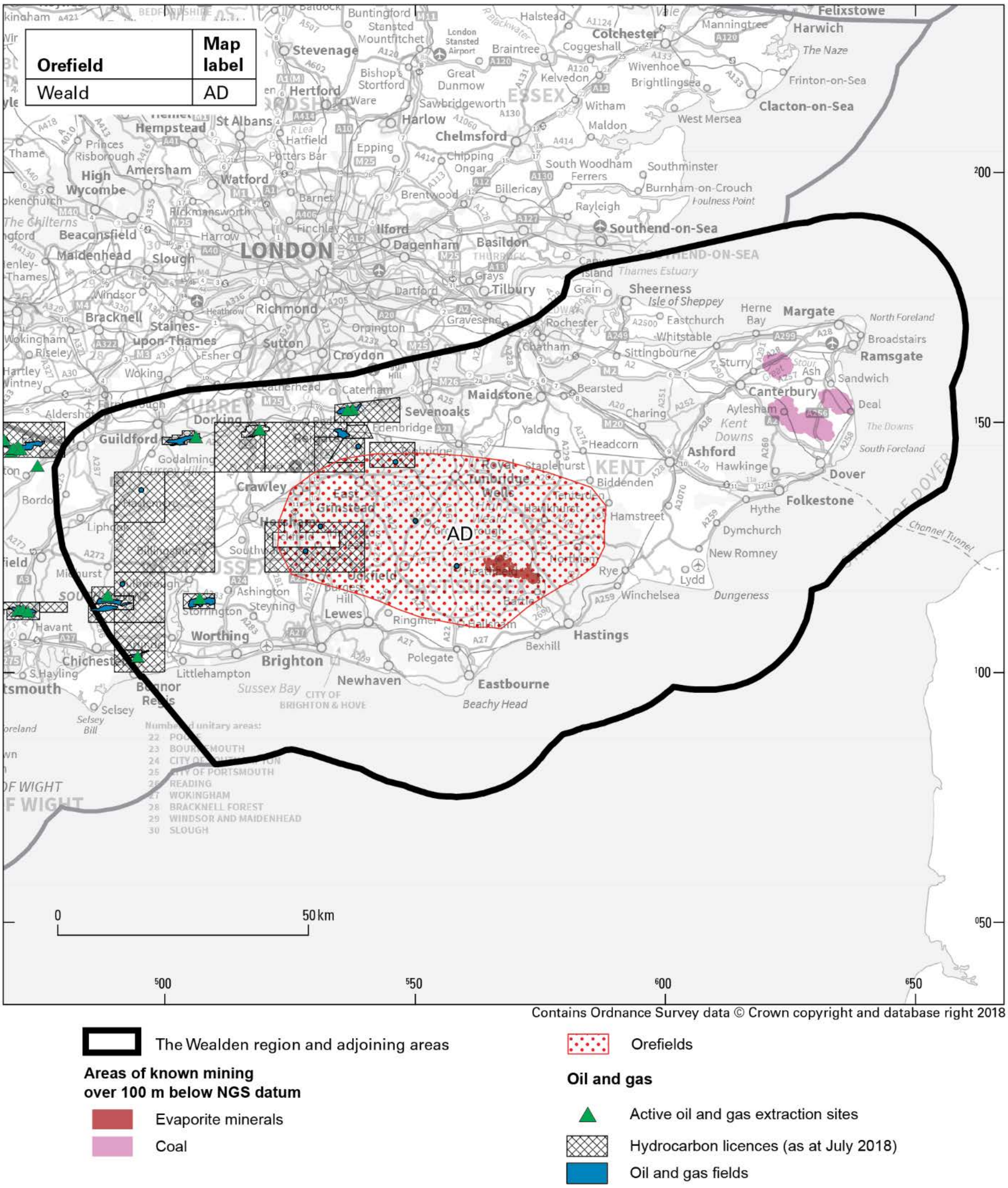


Figure 21 Distribution of mineral resources in the Wealden region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields 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.

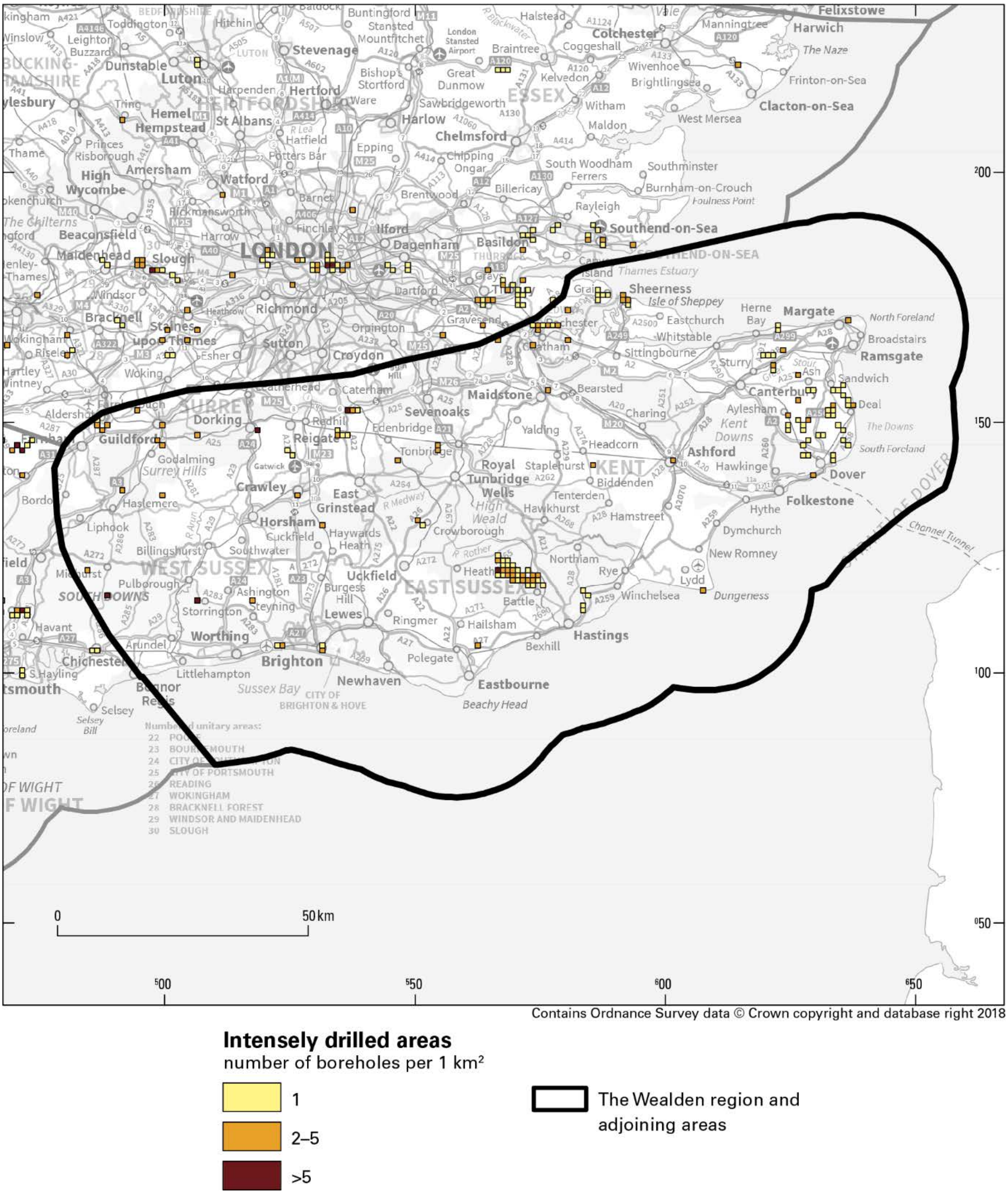


Figure 22 Location of intensely drilled areas in the Wealden region, showing the number of boreholes drilled per 1 km² that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

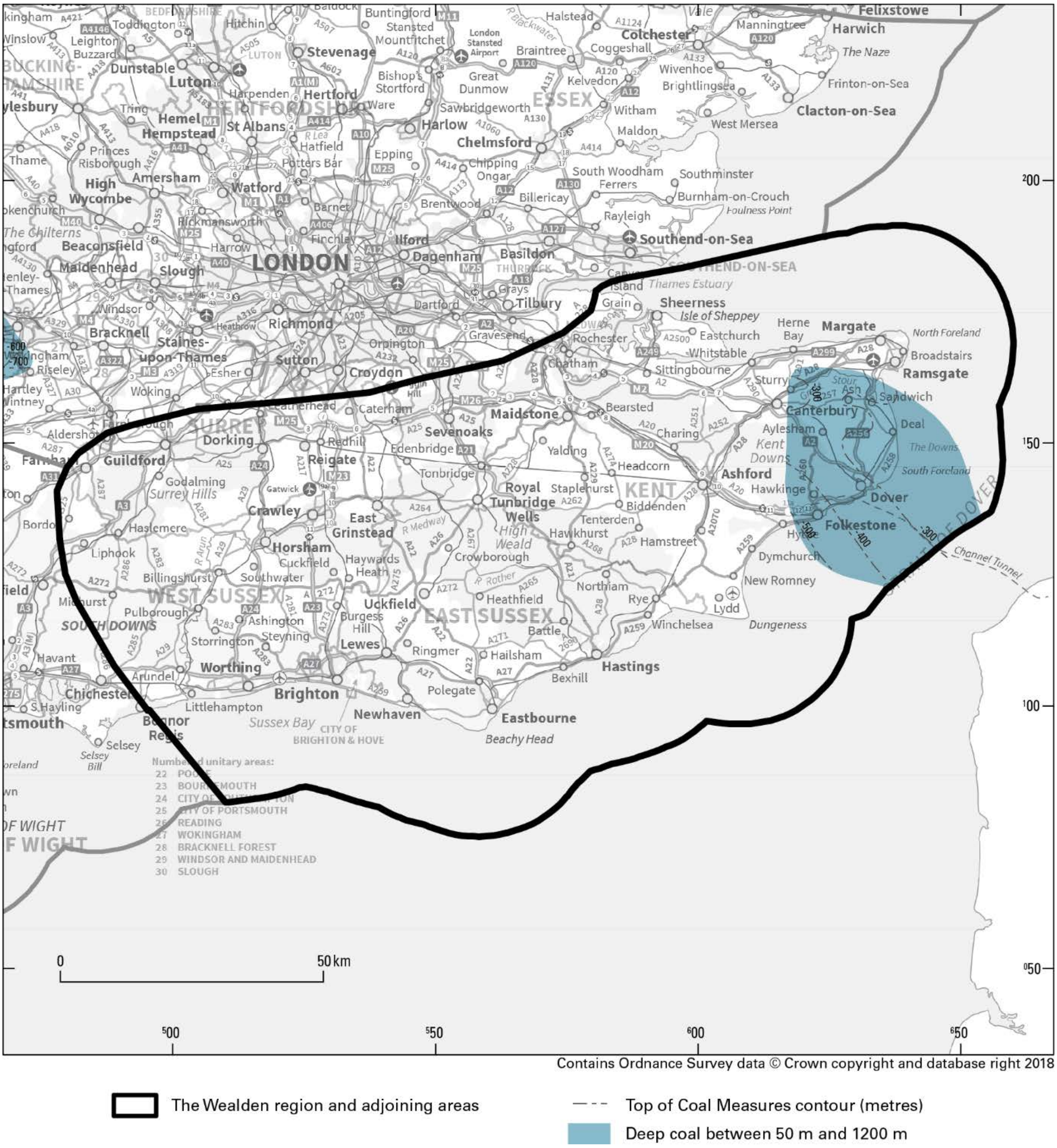


Figure 23 Distribution of coal resources in the region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

8.11 SUPPORTING INFORMATION

8.11.1 Coal and related commodities

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

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

8.11.2 Potash, halite, gypsum/anhydrite and polyhalite deposits

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

8.11.3 Hydrocarbons (oil and gas)

The hydrocarbon fields displayed on Figure 21 are provided by the hydrocarbon industry to the Oil and Gas Authority. They represent the extent of known hydrocarbon resources usually shown by the oil or gas contact with water within the hydrocarbon trap structure. The hydrocarbon licence areas 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.

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

8.11.4 Borehole depths

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

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

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Resources

<u>Coal resources</u>
The locations of coal resources and areas of deep coal mining have been sourced from:

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Other bedded mineral resources

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

Borehole locations

The locations of deep boreholes are from the BGS Single Onshore Borehole Index database. 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.)

Hydrocarbon resources

The locations of onshore and offshore oil and gas licences are available via the DECC website (https://www.gov.uk/topic/oil-and-gas). Underground coal gasification licences are available via the Coal Authority website. (http://mapapps2.bgs.ac.uk/coalauthority/home.html). Information on the locations of prospective areas for shale gas and oil has been sourced from the BGS/DECC regional shale gas studies: http://www.bgs.ac.uk/shalegas/