British Geological Survey
Expert | Impartial | Innovative

National Geological Screening: the Hampshire Basin and adjoining areas

Minerals and Waste Programme

Commissioned Report CR/17/098

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/098

National Geological Screening: the Hampshire Basin and adjoining areas

A Newell[1], D Schofield[1], D E Evans[2], R Haslam[2], M Lewis[3], J P Bloomfield[3], J R Lee[4], B Baptie[4], R P Shaw[5], T Bide[5] and F M McEvoy

[1]Rock type, [2]Rock structure, [3]Groundwater, [4]Natural processes, [5]Resources

Contributors/editors

L P Field, R Terrington, P Williamson, I Mosca, N J P Smith, C Gent, M Barron, A Howard, G Baker, R M Lark, A Lacinska, S Thorpe, H Holbrook, I Longhurst and L Hannaford

Keywords

National geological screening, GDF, Hampshire, Wessex, rock type, structure, groundwater, natural processes, resources

Bibliographical reference

NEWELL, A, SCHOFIELD, D , EVANS, D E, HASLAM, R, LEWIS, M, BLOOMFIELD, J P, LEE, J R, BAPTIE, B, SHAW, R P, BIDE T AND F M MCEVOY. 2018. National Geological Screening: the Hampshire Basin and adjoining areas *British Geological Survey Commissioned Report*, CR/17/098. 77pp.

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of UK Research and Innovation.

British Geological Survey offices

Environmental Science Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales
Tel 0115 936 3241 Fax number removed
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP
Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place, Cardiff CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB
Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House, Swindon SN2 1FL
Tel   01793 444000
www.ukri.org

Website www.bgs.ac.uk
Shop online at   www.geologyshop.com

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

Contents

FIGURES

TABLES

Acronyms and abbreviations

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

Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1 Introduction

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

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

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

2 Background

2.1 NATIONAL GEOLOGICAL SCREENING GUIDANCE

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

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

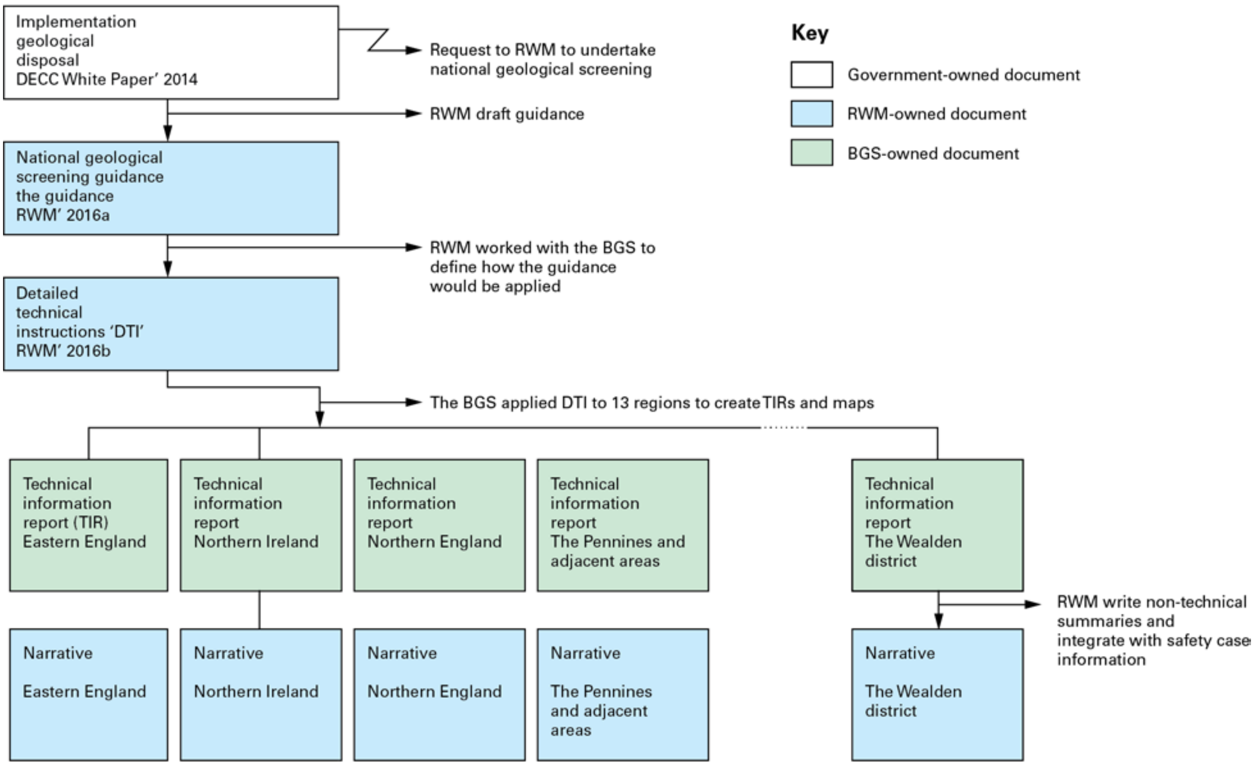


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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

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

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

2.2 DETAILED TECHNICAL INSTRUCTIONS

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

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

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

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

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

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

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

i. **Rock type**

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

ii. **Rock structure**

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

iii. **Groundwater**

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

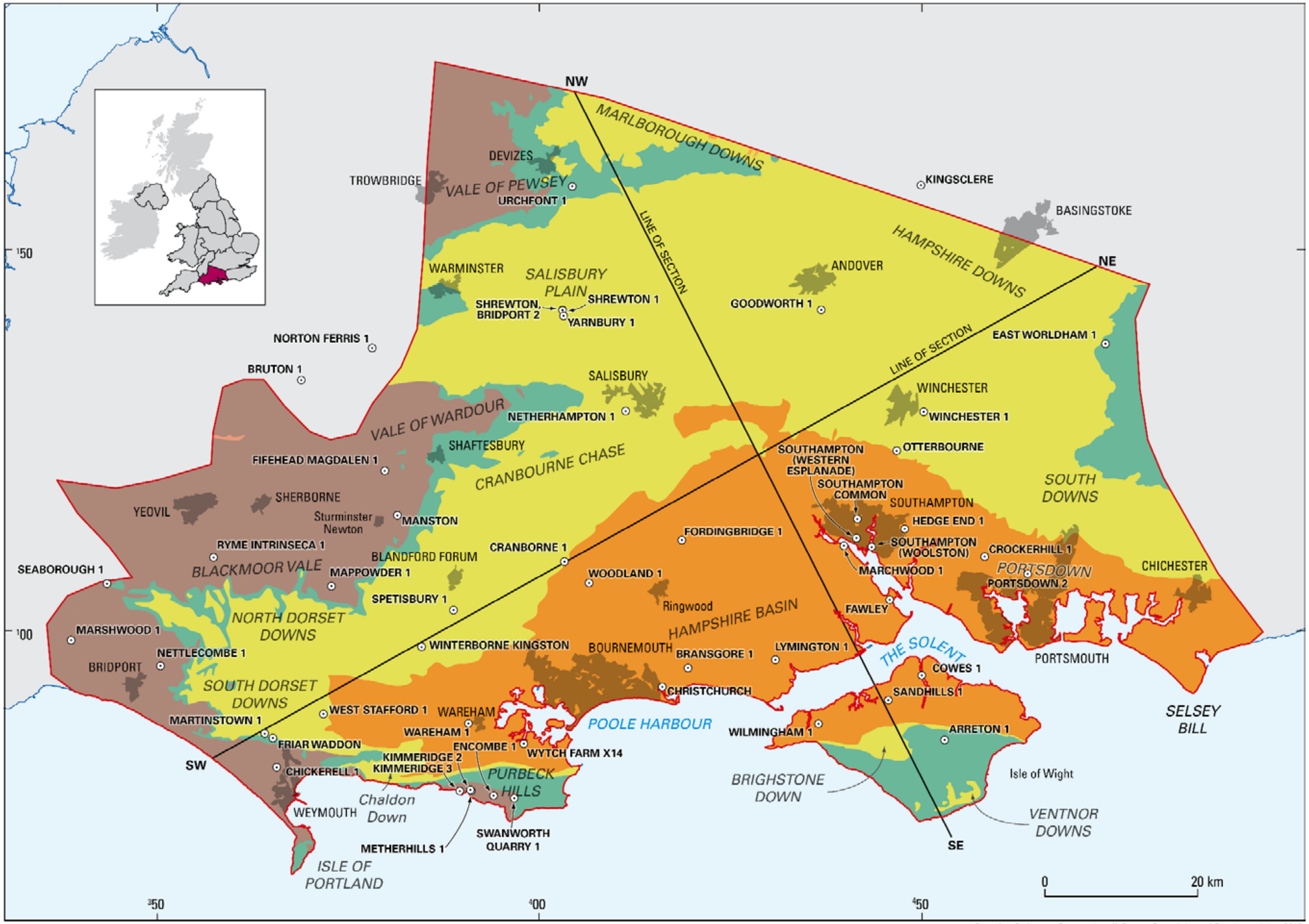
This Hampshire region covers of central southern England including the counties of Hampshire and the Isle of Wight together with significant parts of Wiltshire, Dorset and West Sussex. It is limited to the south by the coast of the English Channel. The region is generally low-lying with ridges, rising up to 300 m.

3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

The geology at surface in the region is shown in Figure 3 and Figures 4 and 5 illustrate the geological variation across the region. The reader is referred to the regional summary on the BGS website (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html) for a non-technical overview of the geology of the region and to national geological screening: Appendix A (Pharaoh and Haslam, 2018) for an account of the formation and structure of the basement, and the older and younger cover rocks of the UK. Principal structural elements of the region are shown in Figure 6.

The Hampshire Basin is a broad structural bowl centred on the Solent, with progressively older strata cropping out away from the centre. In very general terms, the Late Cretaceous Chalk Group forms a large expanse of downland across the north of the region. This is gently inclined to the south and is incised by four main river catchments, the Frome, Stour, Avon and Test. The Chalk dips below younger Palaeogene deposits contained within the Hampshire Basin before resurfacing to form the south Dorset Downs, Purbeck Hills and the central chalk spine of the Isle of Wight (Melville and Freshney, 1982). The narrowness of the Chalk outcrop in south Dorset and the Isle of Wight is a consequence of the generally steep dip of the Chalk toward the north, along a complex zone of folding and faulting often referred to as the ‘Purbeck disturbance’ (Figure 5) (Hamblin, 1992). The Hampshire Basin is thus a large asymmetrical synclinal structure, one of several major, generally west–east trending, fold structures which occur in the region (Melville and Freshney, 1982). All of the folds share a similar genesis having been formed above faults that were reverse-reactivated during Alpine compression of southern England (Chadwick, 1993).

The Cretaceous and Palaeogene deposits, which dominate the outcrop geology of the region, conceal the underlying Jurassic strata. These are only exposed along the western margins of the region where the younger cover has been eroded. Jurassic rocks, together with underlying Permo-Triassic strata, were deposited within a series of generally west–east-trending, fault-bounded basins (Chadwick, 1986). These include the Pewsey, Mere, Dorset and Portland–Wight sub-basins, which together comprise parts of the larger Wessex Basin (Figure 6).



Contains Ordnance Survey data © Crown Copyright and Database rights 2018.

Age (Ma)	Map/section descriptor	Geological sub-units		Text descriptor
35–60	Palaeogene sediments	Solent Group Bracklesham and Barton groups Thames Group Lambeth Group	🟧	Younger sedimentary rocks
70–100	Late Cretaceous sedimentary rocks	Chalk Group	🟨	
100–145	Early Cretaceous sedimentary rocks	Upper Greensand Formation Gault Formation Lower Greensand Group Wealden Group	🟩	
145–205	Jurassic sedimentary rocks	Portland Group Kimmeridge Clay Formation Corallian Group Oxford Clay Formation Oolite groups Lias Group	🟫	
205–290	Permo–Triassic sedimentary rocks	Mercia Mudstone Group Sherwood Sandstone Group Aylesbeare Mudstone Group	🟥	
290–500	Palaeozoic–Precambrian	Coal Measures Group Carboniferous Limestone Supergroup Devonian, Silurian, Ordovician, Cambrian and Precambrian rocks	🟪	Older sedimentary rocks and basement rocks

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

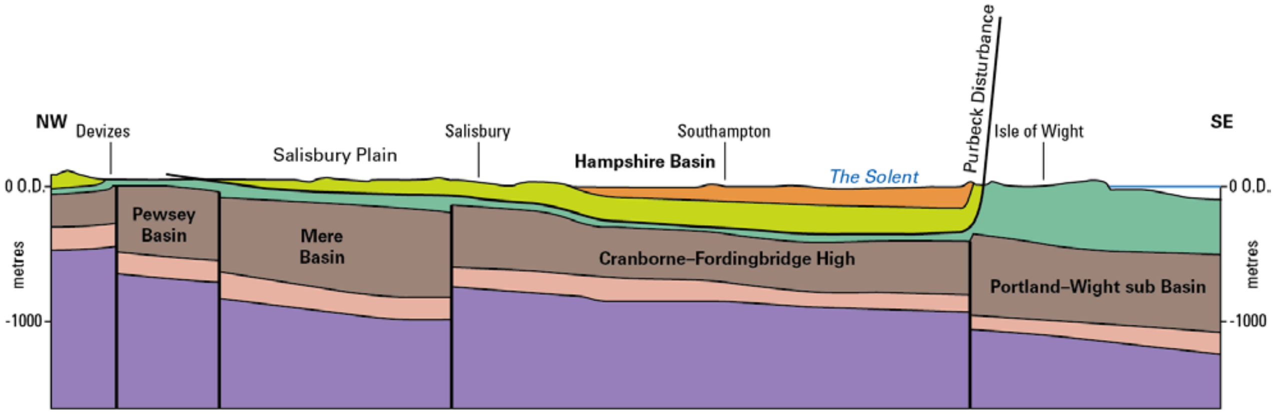


Figure 4 Schematic north-west to south-east cross-section through Hampshire showing the Mesozoic basins of the Wessex Basin and the younger Cenozoic Hampshire Basin. Line of the section and key are shown in Figure 3. British Geological Survey © UKRI 2018.

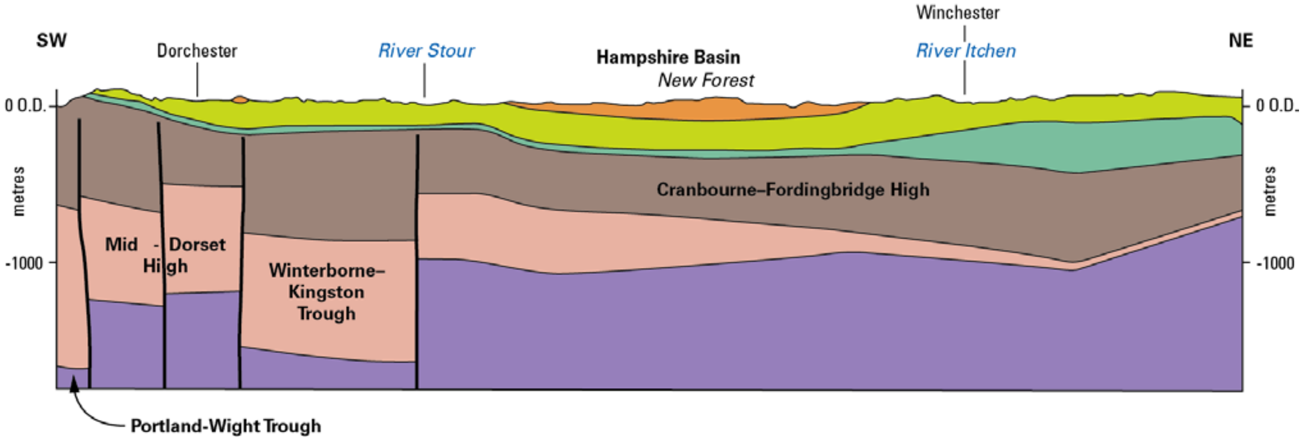


Figure 5 Schematic south-west to north-east cross-section through Hampshire. Line of the section and key are shown in Figure 3. Note there are many variations in naming of identical basins and highs: Cranborne–Fordingbridge high = Hampshire–Dieppe high; Winterborne–Kingston trough = Dorset sub-basin = Cerne–Winterborne–Kingston trough. British Geological Survey © UKRI 2018.

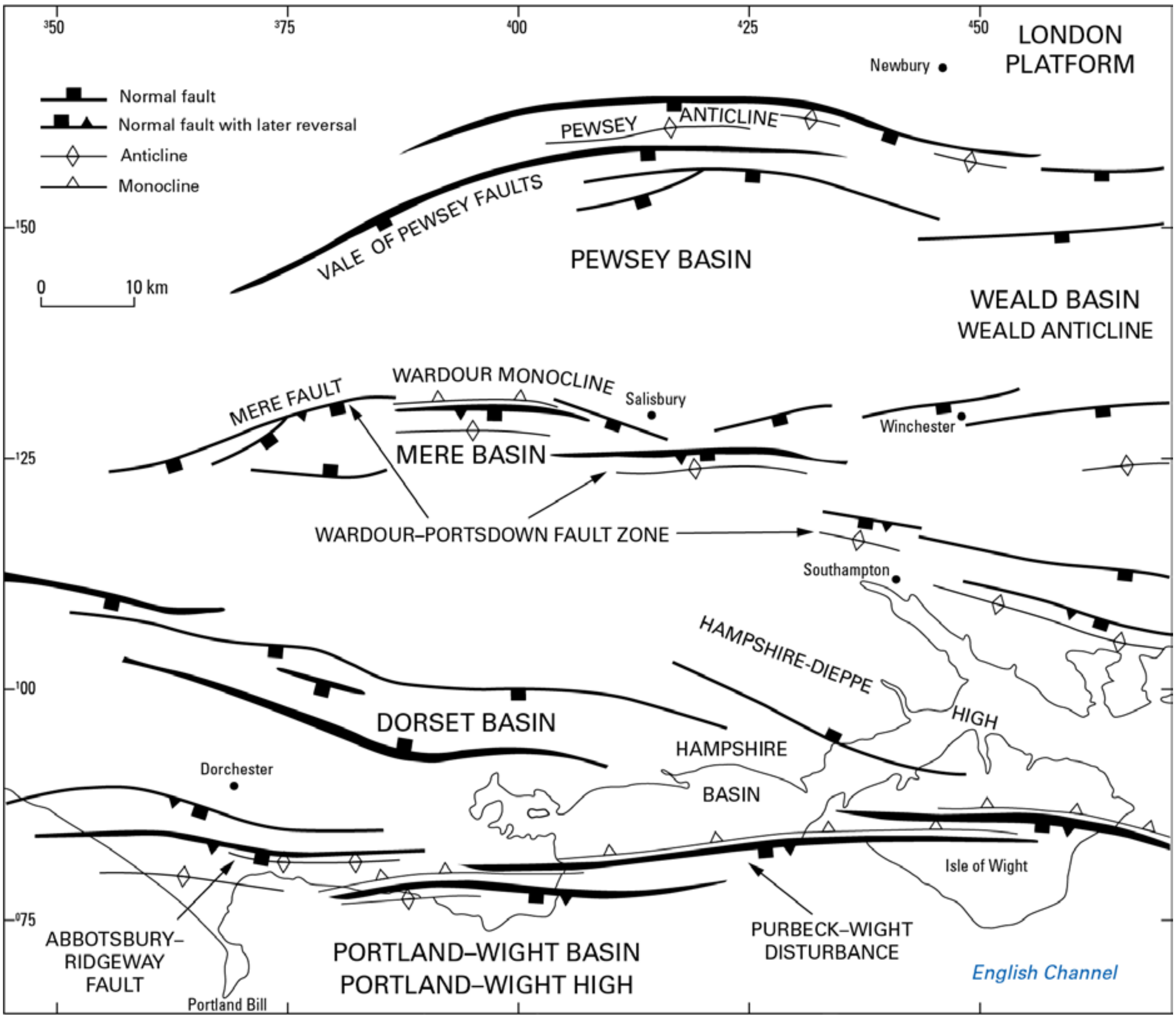


Figure 6 Principal structural elements of the Wessex–Channel basin. Mesozoic extensional structural features on black, Cenozoic compressional features in red (after Evans et al., 2011 and Chadwick and Evans 2005). British Geological Survey © UKRI 2018

3.1.1 Geological data and confidence

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

The Wessex Basin is a mature hydrocarbon exploration province and has a dense coverage of seismic surveys and contains in excess of 50 deep (1–2 km) boreholes, many of which extend into the Triassic Sherwood Sandstone Group, or in some cases early Palaeozoic basement rocks (Whittaker, 1985). Most of these boreholes have geophysical logs, borehole cutting returns and occasionally core descriptions which provide a firm control on the borehole stratigraphy (Whittaker et al., 1985). Geological interpretations in the vicinity of pre-existing boreholes should therefore be reasonably confident. Confidence in the interpretations is likely to be decrease with distances (approximately 10 km) from each deep borehole, which in this region includes parts of Hampshire east of Winchester and parts of Wiltshire to the north and south of Warminster. It is important to note that the Hampshire region contains many geological faults which may cause abrupt changes in the elevation of a geological formation, so proximity to a borehole is not an automatic guarantee of confidence in a geological interpretation. All of the information in the report is based on measured depths assuming vertical borehole paths. While most of the boreholes are close to vertical, a few are deviated so true depths and thickness will differ from those based on measured depth.

4 Screening topic 1: rock type

4.1 OVERVIEW OF THE ROCK TYPE APPROACH

The rock type DTI (RWM, 2016b) sets out how data and information on the topic of rock type are assembled and presented to produce maps for each region showing the ‘distribution of potential host rocks at 200 to 1000 m depth’ and ‘rock formations that surround the host rocks’. For this study, these are combined and referred to as ‘potential rock types of interest’ (PRTIs). Therefore, PRTIs are defined as rock units that have the potential to be host rocks and/or rocks in the surrounding geological environment that may contribute to the overall safety of a GDF. An example of the latter is a mudstone that may be insufficient in thickness to host a GDF but could potentially act as a barrier to fluid flow above the host rock.

The methodology for selecting units as PRTIs is described in the DTI document (RWM, 2016b) and is summarised here. Guided by the safety requirements for a GDF, in the form of selection criteria, lithologies were assigned to each of the generic host rock types as shown in Table 2.

Table 2 Lithologies assigned to each of the generic host rock types. *Definitions of the generic host rock types are provided in the glossary.

Generic host rock type	Selection criteria (where available)	Lithologies to be considered PRTIs
Evaporite*	• halite	Rock-salt
Lower strength sedimentary rocks*	• high clay content (low permeability) • continuous laterally on a scale of tens of kilometres • no minimum thickness • mechanically weak (not metamorphosed)	Clay
		Mudstone
Higher strength rocks*	• low matrix porosity • low permeability • homogeneous bodies on a scale to accommodate a GDF • 80% of the mapped unit must be made up of the specific PRTI	Older compacted and metamorphosed mudstones of sedimentary or volcanic origin within established cleavage belts
		Extrusive igneous rock
		Intrusive igneous rock such as granite
		Metamorphic rock — medium to high grade

The lithologies were extracted from the NGS3D model, a three-dimensional geological model derived from the UK3D v2015 model (Waters et al., 2015) comprising a national network, or ‘fence diagram’, of cross-sections that show the bedrock geology to depths of at least 1 km. The stratigraphical resolution of the rock succession is based on the UK 1:625 000 scale bedrock geology maps (released in 2007) and has been adapted for parts of the succession by further subdivision, by the use of geological age descriptions (i.e. chronostratigraphy rather than lithostratigraphy), and to accommodate updates to stratigraphical subdivisions and nomenclature. Lithostratigraphical units are generally shown at group-level (e.g. Lias Group), or subdivided to formation-level (e.g. Burnham Chalk Formation). Amalgamations of formations are used to accommodate regional nomenclature changes or where depiction of individual formations would be inappropriate at the scale of the model (e.g. Kellaways Formation And Oxford Clay Formation (Undivided)). Chronostratigraphical units are classified according to their age and lithology (e.g. Dinantian rocks – limestone; Silurian rocks (undivided) – mudstone, siltstone and sandstone). Igneous rocks are generally classified on the basis of process of formation, age and lithology (e.g. Unnamed extrusive rocks, Silurian to Devonian - mafic lava and mafic tuff).

The NGS3D (see glossary) was developed from UK3D v2015 including the incorporation of additional stratigraphical detail to allow the modelling of halite units. The NGS3D model was used as an information source for estimating the presence, thickness, depth of occurrence of geological units discussed below, and the geometry of their boundaries. Interpretations based on this model rely on geological relationships depicted in cross-sections, and it is possible that understanding of these relationships in some areas may be limited by cross-section data availability.

The units extracted from the NGS3D model, the PRTIs (see RWM, 2016b for a description of the methodology), were used as the basis for writing the rock type section of this document. For each PRTI, an overview of its distribution, lithology and thickness is given, including information on the variability of these properties, if available, along with references to key data from which the information is derived. Information on the distribution of each PRTI between 200 and 1000 m is guided by the geological sections in the NGS3D model.

4.2 POTENTIAL ROCK TYPES OF INTEREST IN THE HAMPSHIRE REGION

Table 3 presents a generalised vertical section (GVS) for the Hampshire 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 Hampshire region, the GVS groups the rocks into three age ranges: younger sedimentary rocks (Palaeogene to Permian), older sedimentary rocks (Carboniferous) and basement rocks (Devonian and older) (Table 3). The rocks in the region are predominantly sedimentary in origin. In general terms, strata older than the Early Cretaceous Lower Greensand are inclined to the east across the Hampshire region so that progressively older strata tend to occur within the depth range of interest between 200 to 1000 m below NGS datum within north–south orientated belts that migrate progressively to the west (Whittaker, 1985). Deposits younger than the Lower Greensand overlie the major late Cimmerian unconformity (Hamblin, 1992). Together with the effects of basin inversion and folding, the late Cimmerian unconformity profoundly modifies the distribution of these deposits within the depth range of interest. The late Cimmerian unconformity introduces additional complication because of the variable erosion of underlying deposits which is concealed at subcrop (Whittaker, 1985).

Some of the rock units in the region are considered to represent PRTIs present within the depth range of interest, between 200 and 1000 m below NGS datum. These are predominantly lower strength sedimentary rock (LSSR) PRTIs and one evaporite (EVAP) PRTI within the younger sedimentary rocks and one higher strength rock (HSR) PRTI in the basement rocks. Carboniferous rocks and early Palaeozoic rocks in the region (comprising Early Devonian, Silurian, Ordovician and Cambrian rocks), although largely lying within the established Variscan cleavage belt, are deeper than the depth range of interest and are therefore not considered PRTIs and are not discussed further. A narrow belt of mudstone-dominated HSR does however occur within the depth range of interest in the north-west of the region and is described below.

The PRTIs are described in Table 3 in stratigraphical order from youngest to oldest (i.e. in downward succession), grouped by the three age ranges: younger sedimentary rocks and older sedimentary rocks. The descriptions include the distribution of the PRTI at surface (outcrop) and where the PRTI is present below the surface (subcrop) within the depth range of interest, along with key evidence for the interpretations. The main geological properties of the PRTIs and how these vary across the region are also summarised. Data are mostly taken from the BGS Regional Guide to the Hampshire Basin and adjoining areas (Melville and Freshney, 1982) 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 report are shown on Figure 3.

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

Maps showing the lateral distribution of PRTIs for the three generic host rock types between 200 and 1000 m below NGS datum are provided in Figures 7, 8 and 9. A summary map showing the combined lateral extent of all PRTIs is provided in the region is provided in Figure 10.

Table 3 Schematic GVS for the Hampshire 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 7, 8 and 9 for the regional distribution of PRTIs amalgamated by host rock type (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**	Solent Group	Clay, silt, sand, limestone	N/A	North Isle of Wight and adjacent parts of the mainland	N/A	
		Bracklesham and Barton groups	Sand, silt, clay, ferruginous sandstone, limestone	N/A	North Isle of Wight and adjacent parts of mainland	N/A	N/A
		Thames Group	Clay, silt, sand and gravel	N/A	North Isle of Wight and adjacent parts of mainland	N/A	N/A
		Lambeth Group	Clay, silt, sand and gravel	N/A	North Isle of Wight and adjacent parts of mainland	N/A	N/A
	Cretaceous	Chalk Group	Soft, fine-grained limestone, with thin mudstone units and flint	N/A	N/A	N/A	Chalk Group
		Upper Greensand Formation (Selborne Group)	Siltstone, sandstone and clayey sandstone	N/A	N/A	N/A	Upper Greensand Formation
		Gault Formation (Selborne Group)	Mudstone and silty mudstone	N/A	Gault Formation (within depth range of interest around Dorchester to Portsmouth)	N/A	N/A
		Lower Greensand Group	Sandstone	N/A	N/A	N/A	Lower Greensand Group (Folkestone and Hythe formations)
		Wealden Group	Mudstone, silty mudstone, siltstone, sandstone, clay-ironstone and thin limestones	N/A	Weald Clay Formation, Grinstead Clay Member, Wadhurst Clay Formation	N/A	N/A
	Jurassic–Cretaceous	Purbeck Group	Interbedded limestone and mudstone	N/A	N/A	N/A	N/A
	Jurassic	Portland Group	Limestone, sandstone, subordinate mudstone	N/A	N/A	N/A	Portland Stone Formation
		Kimmeridge Clay and Ampthill Clay formations (undivided)	Predominantly mudstone, with subordinate siltstones, sandstones and thin muddy limestones	N/A	Kimmeridge Clay Formation	N/A	N/A
		Corallian Group	Limestone, sandstone, siltstone and mudstone	N/A	Corallian Group (mudstone-rich parts)	N/A	N/A
		Oxford Clay and Kellaways formations (undivided)	Mudstone, siltstone and thin silty limestone at some levels	N/A	Oxford Clay and Kellaways formations	N/A	N/A
		Great Oolite Group	Sandstone, limestone and argillaceous rocks	N/A	Frome Clay and Fuller's Earth formations	N/A	Great Oolite Group (amalgamated limestones in north)
		Inferior Oolite Group	Limestone, sandstone, siltstone and mudstone	N/A	N/A	N/A	Inferior Oolite Group
		Lias Group	Mudstone, siltstone, limestone and sandstone	N/A	Lias Group	N/A	Bridport Sand Formation
	Triassic	Mercia Mudstone Group (including Penarth Group in UK3D)	Mudstone, siltstone, halite, anhydrite, sandstone	N/A	Mercia Mudstone Group including Penarth Group	Dorset Halite Member	Mercia Mudstone Group marginal facies
		Sherwood Sandstone Group	Conglomerate and sandstone	N/A	N/A	N/A	Sherwood Sandstone Group
	Permian	Permian Rocks undiff= Aylesbeare Mudstone Group	Mudstone, sandstone and breccia	N/A	Aylesbeare Mudstone Group	N/A	N/A
OLDER SEDIMENTARY ROCKS	**Carboniferous**	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
		Tournasian–Visean rocks= Carboniferous Limestone Supergroup	Limestone with interbedded mudstones	N/A	N/A	N/A	Carboniferous Limestone Supergroup
		Teign Valley and Tintagel groups	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
BASEMENT ROCKS	**Devonian**	Devonian rocks (undivided)	Mudstone, sandstone, phyllite, slate, limestone	Within depth range of interest in north-west of region only	N/A	N/A	N/A
	Precambrian to early Palaeozoic	Silurian rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Cambrian and Ordovician rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Proterozoic to Palaeozoic rocks (undivided) – varied	Varied Including sedimentary rocks and minor igneous rocks	N/A	N/A	N/A	N/A

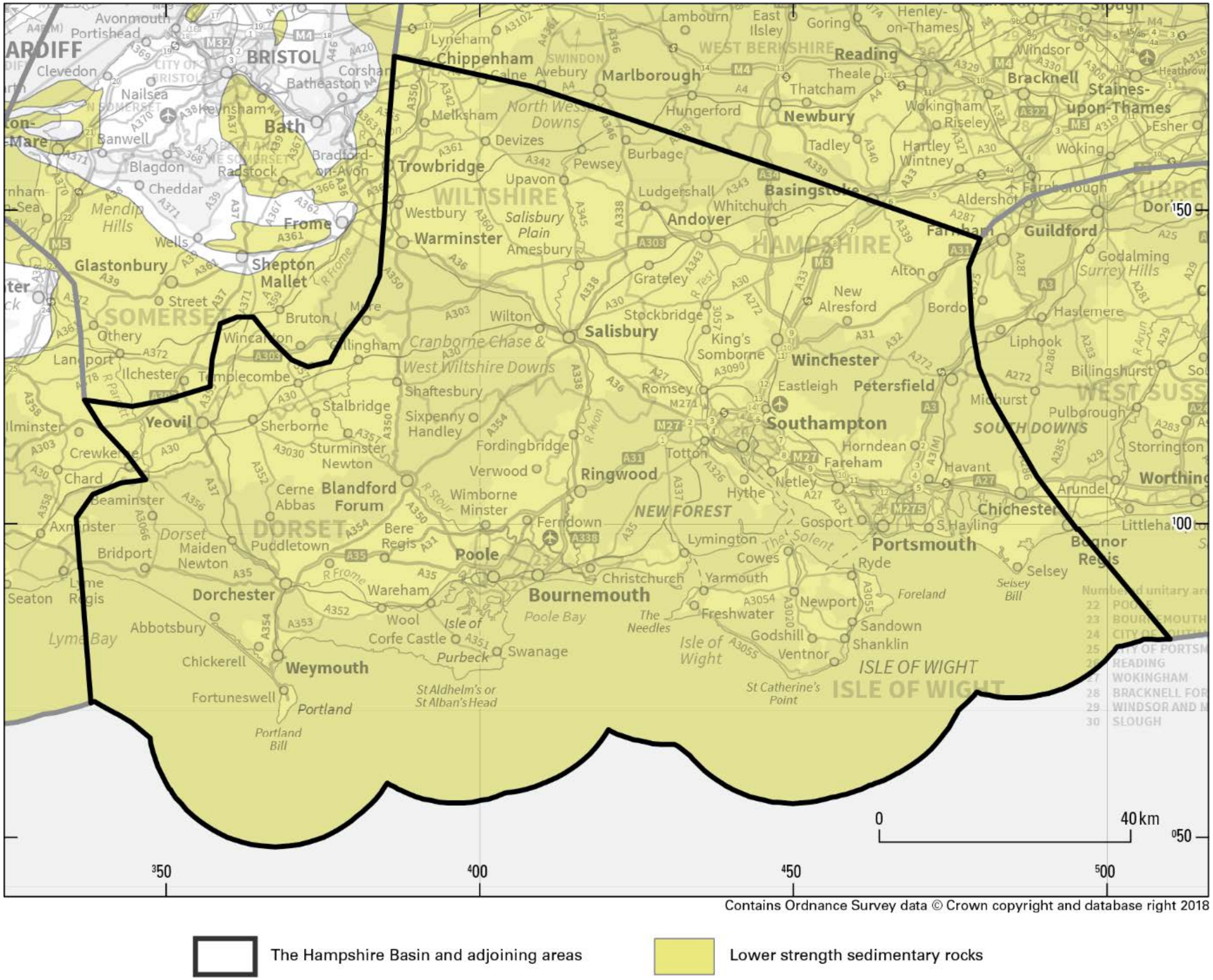
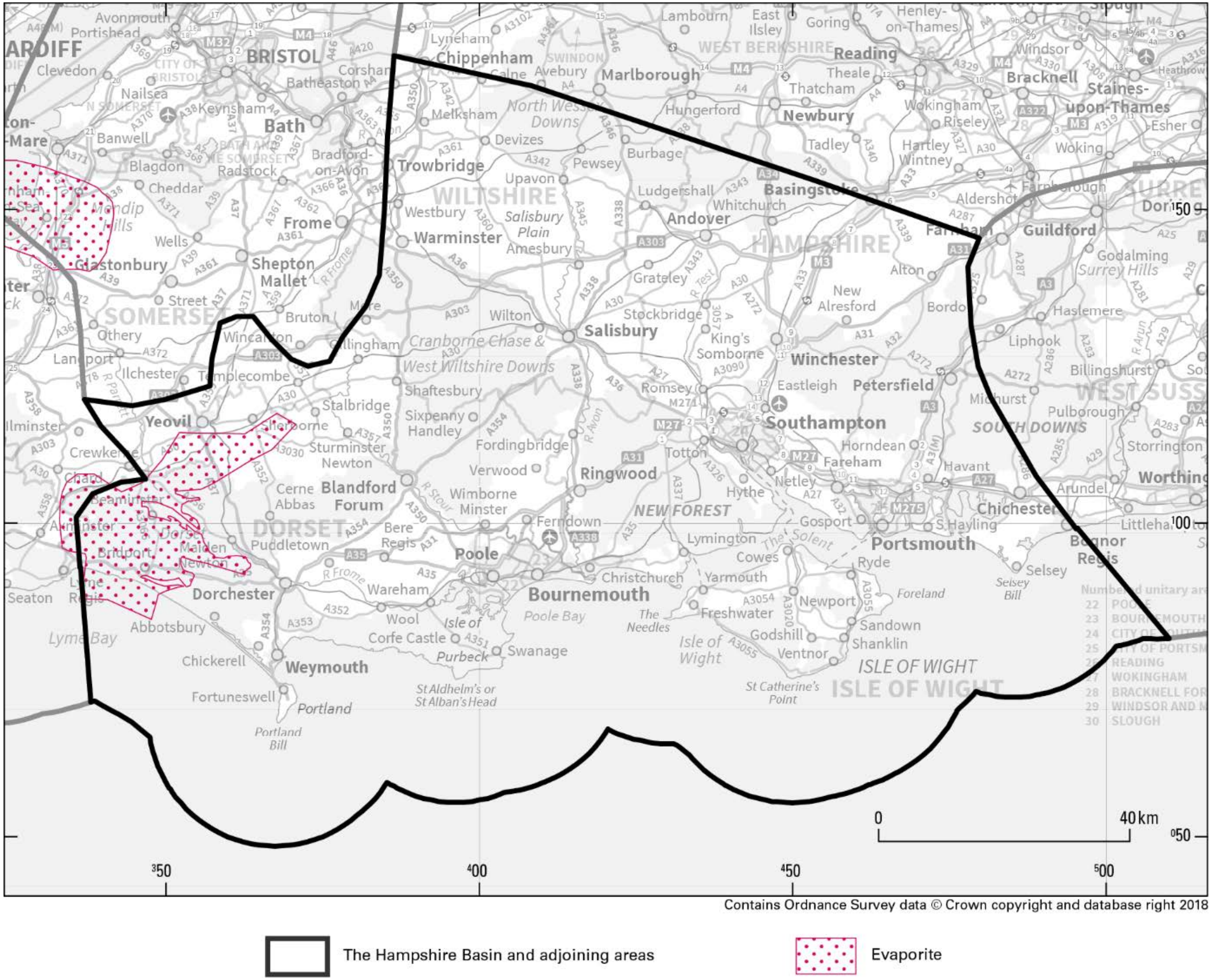
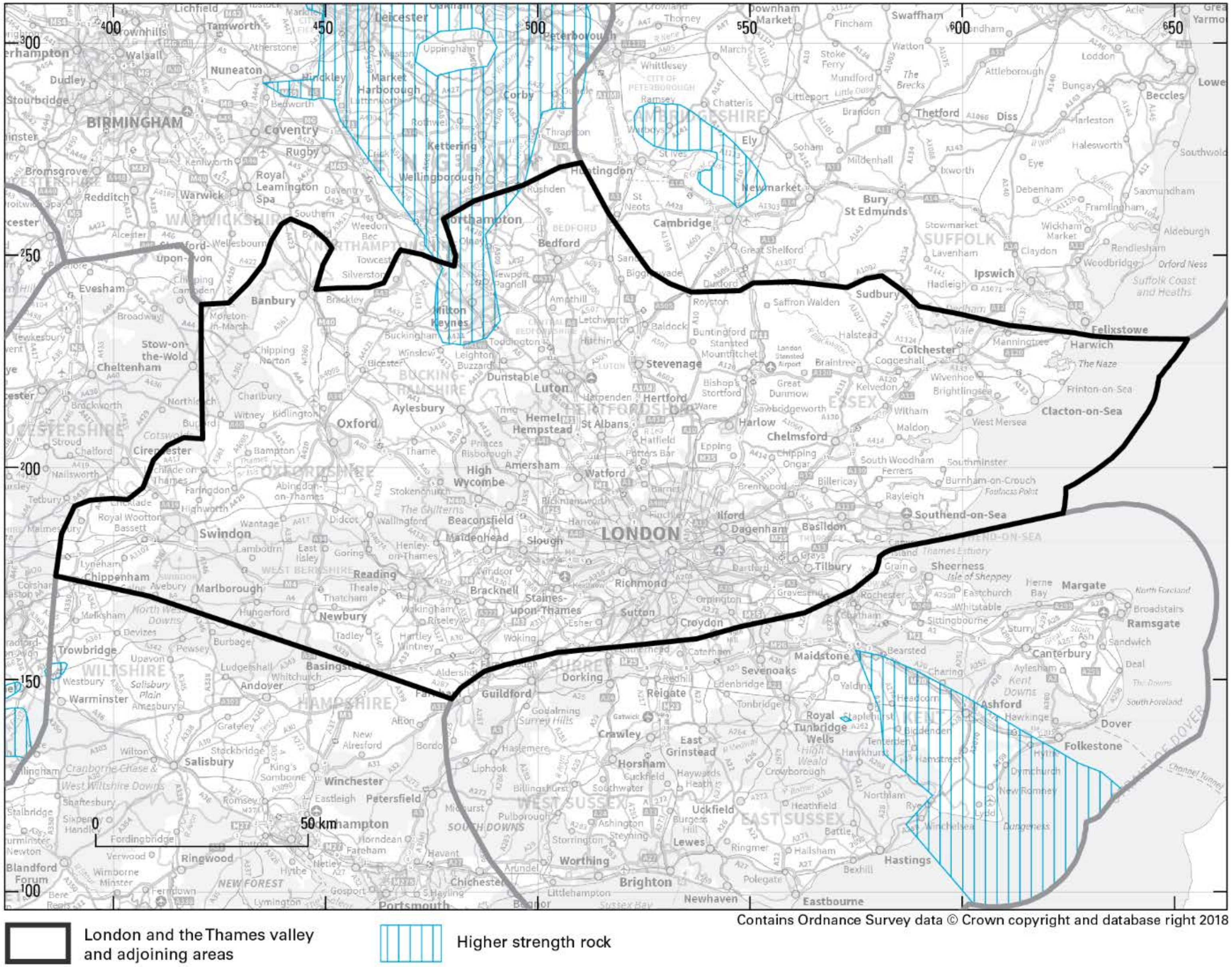

Contains Ordnance Survey data © Crown copyright and database right 2018

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



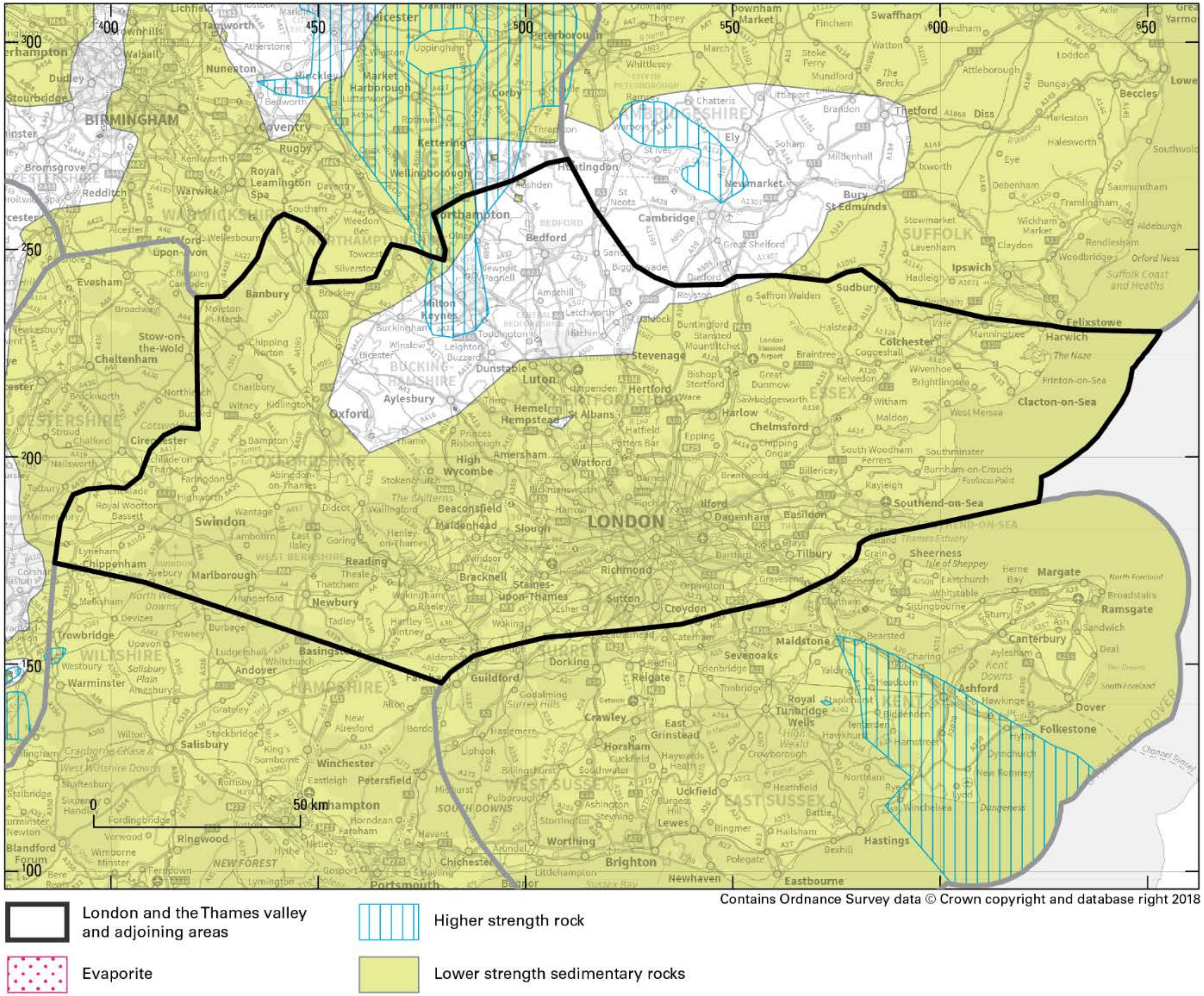
Contains Ordnance Survey data © Crown copyright and database right 2018

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



Contains Ordnance Survey data © Crown copyright and database right 2018

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



Contains Ordnance Survey data © Crown copyright and database right 2018

Figure 10 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Hampshire 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 UNDIVIDED PALAEOGENE SOLENT, BARTON AND BRACKLESHAM GROUPS; THAMES AND LAMBETH GROUPS — LSSR

Distribution and thickness

Palaeogene deposits occur within the core of the Hampshire Basin, a strongly asymmetrical syncline with a gently sloping northern limb and a steep, near-vertical, southern limb along the Purbeck disturbance (Hamblin, 1992). The oldest Palaeogene deposits comprise the Lambeth Group. These unconformably overlie the Chalk and crop around the periphery of the Palaeogene outcrop. The younger deposits of the Solent Group occupy a south, central position within the basin, cropping out on the northern half of the Isle of Wight and adjacent parts of mainland Hampshire (Freshney, 1987; Hopson, 2011). Due to tectonic folding, the base of the Palaeogene deposits reaches a maximum depth of around 650 m below OD on the Isle of Wight, however over much of mainland Hampshire the base of the Palaeogene is generally less than 200 m from surface (Bristow et al., 1990, Melville and Freshney, 1982). Folds bring Palaeogene deposits close to surface in east Hampshire and cause localised exposure of the underlying Chalk Group (Freshney, 1987). Mudstone units within the Lambeth, Thames, Bracklesham and Solent groups thus occur within the depth range of interest only over a relatively small area, encompassing the northern half of the Isle of Wight and adjacent parts of mainland Hampshire in the area between Lymington, Christchurch, Ringwood and Southampton Water.

Principal information sources

The primary source of information for the Palaeogene comes from coastal exposures on the Isle of Wight, including the type sections at Alum Bay and Whitecliff Bay (Hopson, 2011). Palaeogene deposits are also well known from cored boreholes at Christchurch (Bristow et al., 1990) and deep hydrocarbon or geothermal energy exploration boreholes such as Cowes 1 and Wilmingham 1 on the Isle of Wight and Bransgore 1, Lymington 1 and Marchwood 1 (Whittaker et al., 1980) on the mainland.

Rock type descriptions

Palaeogene deposits are a complex admixture of sand and clay with much lateral and vertical variation over short distances which can make their precise correlation in the subsurface problematic.

The Solent Group includes a number of mud-rich intervals, notably the Osborne Member and the Hamstead Member, however their distribution is largely limited to the Isle of Wight (Hopson, 2011) at depths that are mostly shallower than the depth range of interest.

The Barton Clay Formation is 67 m thick at its type section near Barton-on-Sea but ranges up to 111 m thick at Whitecliff Bay (Melville and Freshney, 1982). The formation mostly comprises muds, glauconitic sandy muds and sands locally containing much shell debris. The formation coarsens upwards into the overlying Chama Sand and Becton Sand formations (Melville and Freshney, 1982).

The Bracklesham Group is a predominantly sandy sequence with intervals of mud or mudstone rarely exceeding a few metres. Most of the muds in the Bracklesham Group are finely interlaminated with sand (Freshney, 1987).The Thames Group ranges up to 100 m thick in the Hampshire Basin. The primary lithology is a grey mud which is often sandy and grades upwards into sands and interbedded sands and muds through a series of coarsening-upwards cycles (Melville and Freshney, 1982). The principal London Clay Formation subdivision of the Thames Group in the Hampshire Basin is much sandier than that found in the London basin and grades into the overlying Bracklesham Group.

The Lambeth Group is typically 20–50 m thick and comprises brown, grey and red-mottled muds with variable amounts of sand which locally can represent over half of the formation (Melville and Freshney, 1982; Freshney, 1987). The Lambeth Group is absent from areas to the west of Poole Harbour (Bristow et al., 1990).

4.2.1.2 GAULT FORMATION — LSSR

Distribution and thickness

The Gault Formation occurs across much of the Hampshire region where it forms part of an Early Cretaceous sequence that includes the Lower Greensand Group and Upper Greensand Formation. These rocks overlie the late Cimmerian unconformity and its distribution is markedly different from pre-unconformity strata such as the Wealden Group. The outcrop of the Gault Formation occurs in four main areas, as a narrow strip flanking the western edge of the Chalk outcrop in Wiltshire and Dorset, across the southern half of the Isle of Wight and along the escarpment of the Hampshire Downs adjacent to the Weald (Hopson et al., 2008). Along the Purbeck Fault (shown on Figure 13) the Gault Formation has a narrow outcrop and dips steeply northward into the Hampshire Basin (Barton et al., 2011; Hamblin, 1992). From outcrop, the base of the Gault Formation dips centripetally toward a low point in the north-west Isle of Wight, where it reaches a depth of approximately 1 km just to the north of the Sandhills 1 Borehole (Whittaker, 1985). The Gault Formation occurs above 200 m below OD over large parts of north Hampshire, Wiltshire and south Dorset because of the low structural dip in this area. The Gault Formation occurs within the depth range of interest in a subcircular area that encompasses Dorchester, Blandford Forum, Salisbury, Andover, Winchester, Southampton and Portsmouth.

On the Dorset coast the thickness of the Gault Formation fluctuates from 7.3–27.7 m (Melville and Freshney, 1982). Inland, it thickens northward to over 27 m in the vales of Wardour and Pewsey. Boreholes show it is 52 m thick beneath the Chalk Group in the upper Kennet valley and 86.5 m at Kingsclere. The Gault Formation thins to 17 m or less westwards into south Dorset and Wiltshire where it has a diachronous relationship with the Upper Greensand Formation. In the Winterborne Kingston borehole, the Gault Formation is 21.62 m thick (Rhys et al., 1982).

Principal information sources

The Gault Formation is well known from coastal exposures on the Isle of Wight (Hopson, 2011) and from numerous boreholes across the Hampshire region (Melville and Freshney, 1982). Fragmentary core of the Gault Formation was recovered from the Winterborne Kingston Borehole (Rhys et al., 1982).

Rock type descriptions

The Gault Formation is primarily dark grey-green, micaceous silty clay. The junction with the Upper Greensand Formation is typically transitional with the development of dark grey argillaceous sandstone.

4.2.1.3 WEALDEN GROUP — LSSR

Distribution and thickness

The Wealden Group has a relatively small area of outcrop and subcrop in the Hampshire region. The principal outcrops occur along the south Dorset coast around Weymouth and Swanage, with further exposures of the Wealden Group on the southern part of the Isle of Wight (Hopson, 2011). Across the remainder of the region, the only other outcrops are in the Vale of Wardour. From outcrop, the base of the Wealden Group dips toward the east reaching a depth of around 1000 m below OD in east Hampshire. The base of the Group was proved at 827.9 m (measured depth) in the East Worldham 1 Borehole. The Wealden Group occurs within the depth range of interest under the Hampshire Downs and South Downs north-east of Salisbury and Southampton, and in the southern part of the Isle of Wight. The Wealden Group ranges up to 500 m thick in the northern Hampshire region, 580 m on the Isle of Wight, 800 to 1000 m thick at Swanage, 425 m at Worbarrow Bay and 65 m at Durdle Cove, the Group's most westerly coastal outcrop (Melville and Freshney, 1982). Across much of Dorset and west Hampshire the Wealden Group has been removed by erosion beneath the Early Cretaceous unconformity (Whittaker, 1985).

Principal information sources

The Wealden Group is well exposed along the south Dorset coast between Weymouth and Swanage and at the type sections on the southern coast of the Isle of Wight where 305 m out of a total thickness of 612 m are exposed (Melville and Freshney, 1982). It was proved in a number of deep boreholes within the depth range of interest including Arreton 1, Crockerhill 1, Hedge End 1, Goodworth 1 and East Worldham 1 (where the thickest Wealden Group is present).

Rock type descriptions

The Wealden Group is dominated by interbedded thick sandstones, siltstones, mudstones, limestones and clay ironstones of predominantly non-marine type. On the Isle of Wight and adjacent parts of the south Dorset coast two distinct divisions can be recognised, the Vectis Formation (Wealden Shales) and the Wessex Formation (Wealden Marls) (Hopson, 2011; Hopson et al., 2008). The Vectis Formation is approximately 66 m thick and comprises dark grey siltstones and mudstones with subordinate beds of sandstone, shelly limestone, clay ironstone and ironstone. In the East Worldham 1 Borehole, adjacent to the Weald basin, cuttings and gamma-ray logs indicate a predominance of mudstone at the base (‘Fairlight Clay’) coarsening progressively upwards in the sandier succession of the ‘Ashdown Sands’. The Wessex Formation is 800–1000 m thick and comprises varicoloured (mainly red) mudstones with subordinate unconsolidated sandstones (generally white or pale yellow as well as red) and some ironstones. Westward, on the mainland through Dorset, sandstone units thicken and include some significant coarse sand and pebble beds.

4.2.1.4 UNDIVIDED AMPTHILL CLAY AND KIMMERIDGE CLAY FORMATIONS — LSSR

Distribution and thickness

The Ampthill Clay and Kimmeridge Clay formations occur undivided in NGS3D however it is only the latter that occurs in the region and is a PRTI and described here. The Kimmeridge Clay Formation crops out along the western part of the region, extending northwards from Mappowder and swinging eastwards into the Vale of Wardour, where the outcrop belt reaches some 10 km wide. It is also exposed at type section along the south Dorset coast (Cox and Gallois, 1981). From outcrop, it dips progressively east with the top reaching a maximum depth of around 1000 m below OD in east Hampshire. Some parts of the Kimmeridge Clay Formation thus lie within the depth range of interest across much of the Hampshire region in the area to the east of Blandford Forum and Warminster.

At its coastal type section in south Dorset, the Kimmeridge Clay Formation can reach 500 m thick (Cox and Gallois, 1981) but across most of the region the Kimmeridge Clay Formation is typically around 200–250 m thick (Whittaker, 1985). The formation is entirely removed along an axis extending from Dorchester toward Lymington and is truncated beneath the Early Cretaceous unconformity over large parts of Hampshire to the south of Salisbury and to the west of Southampton (Whittaker et al., 1985). In the Winterborne Kingston 1 Borehole the Kimmeridge Clay Formation and the Ampthill Clay Formation equivalent (delimited only on microfaunal evidence) were 68.7 m thick below the Early Cretaceous unconformity, which is overlain by the Lower Greensand Group (Rhys et al., 1982).

Principal information sources

The Kimmeridge Clay Formation is well known from its type area at the coastal cliffs between Weymouth and Swanage in south Dorset (Wright and Cox, 2001). Inland it is poorly exposed but is known from numerous deep hydrocarbon exploration boreholes where the Kimmeridge Clay Formation is within the depth range of interest including Cranborne 1, Netherhampton 1 and Urchfont 1. A short section of the Kimmeridge Clay Formation was cored in the Winterborne Kingston 1 Borehole (Rhys et al., 1982). The formation was fully cored in two research boreholes (Swanworth Quarry 1 and Metherhills 1) on the Dorset coast (Morgans-Bell, 2001).

Rock type descriptions

The Kimmeridge Clay Formation comprises alternating beds of dark grey mudstone, highly calcareous mudstone, siltstone, silty mudstone, bituminous mudstone (oil shale) and limestone (Cox and Gallois, 1981). The relative proportion of the different lithologies varies throughout the formation. The upper half of the formation is dominated by calcareous mudstones which pass upwards into siltstones at around 30 m below the contact with the overlying Portland Group (Barton et al., 2011). In the lower half of the formation mudstones are predominant, passing upwards into an interval rich in bituminous shales.

4.2.1.5 CORALLIAN GROUP — LSSR

Distribution and thickness

The Corallian Group forms a curved outcrop belt that passes north of the Dorset Downs through Sturminster Newton. The Corallian Group also crops out around Weymouth where it occurs on opposing limbs of the west–east trending Weymouth Anticline (Barton et al., 2011). In the subsurface, the Corallian Group generally dips to the east, reaching a maximum depth of around 1200 m below OD in east Hampshire (Whittaker et al. 1985). The Corallian Group occurs within the depth range of interest in a broad north–south trending belt which extends northward from Bournemouth and is bounded by Warminster in the west and Southampton in the east.

The Corallian Group ranges up to around 80 m thick, with the thickest successions found in south Dorset. In the Winterborne Kingston 1 Borehole the Corallian Group was 49.9 m thick (Rhys et al., 1982). Elsewhere across the region the Corallian Group is typically 40 m or less (Wright and Cox, 2001). The Corallian Group is extensively eroded beneath the Early Cretaceous unconformity along an axis which extends from Dorchester to Lymington.

Principal information sources

The Corallian Group is well known from coastal outcrops around Weymouth (Wright and Cox, 2001; Barton et al., 2011) and from small exposures inland around Shaftesbury and Wincanton (Bristow et al., 1995; 1999). It has been proven in numerous deep hydrocarbon exploration boreholes such as Woodland 1, Netherhampton 1 and Urchfont 1 and, by virtue of forming a strong seismic reflector, has been mapped widely in the numerous seismic sections that cross the Hampshire region (Chadwick, 2005).

Rock type descriptions

The Corallian Group is a complex succession of interdigitating limestones, marls, sandstones, sands, siltstones, silts, spiculites and mudstones (Wright and Cox, 2001). Mudstones are typically a minor component, with the two principal units (Sandsfoot Clay and Nothe Clay members and their lateral correlatives) rarely exceeding 15 m in thickness. The Sandsfoot Clay Member is a variable unit ranging from sand-free clay through clayey fine-grained sand, to sand, ferruginous sandstone and limonitic oolite. The Nothe Clay Member is a grey mudstone and sandy mudstone, containing scattered ooids, interbedded with about eight limestone horizons. The limestones are variously iron-rich, ooidal, sandy and bioclastic, and there is a distinctive white-weathering shelly micrite, with extensive borings, near the base of the succession. The lower boundary is of a transitional nature with the Oxford Clay Formation.

4.2.1.6 UNDIVIDED KELLAWAYS AND OXFORD CLAY FORMATIONS— LSSR

Distribution and thickness

The Kellaways Formation and Oxford Clay Formation occur undivided in NGS3D. The Oxford Clay Formation has a north–south trending outcrop belt which extends from Weymouth in the south to Wincanton in the north. The continuity of the belt is broken under the South and North Dorset Downs where the Oxford Clay Formation has been eroded beneath the Early Cretaceous unconformity. Around Weymouth, the Oxford Clay Formation forms an arcuate belt around the core of the west–east trending Weymouth Anticline. To the east of the outcrop belt the Oxford Clay Formation dips to the east, with the top reaching a maximum depth of around 1200 m below OD in east Hampshire. The Oxford Clay Formation is within the depth range of interest in a broad, north–south trending belt that extends from Swanage to Devizes and lies to the west of Southampton and to the east of Warminster.

The Oxford Clay Formation ranges up to approximately 185 m thick with the thickest successions in south Dorset. In the Winterborne Kingston 1 Borehole the Oxford Clay Formation was 169.10 m thick (Rhys et al., 1982). Outside this area the Oxford Clay Formation maintains a fairly uniform thickness of around 100–150 m (Whittaker, 1985). The formation is eroded entirely beneath the Early Cretaceous unconformity in the area around Wareham and in the north–west quadrant of the Isle of Wight and adjacent areas (Whittaker, 1985).

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 the Kellaways Clay Member and the Kellaways Sand Member.

Principal information sources

The Oxford Clay Formation is generally poorly exposed, but is known from coastal outcrop around Weymouth (Barton et al., 2011) and is proved within the depth range of interest from numerous deep boreholes including Winterborne Kingston (Rhys et al., 1982), Spetisbury 1 and Shrewton 1 (Whittaker, 1980).

Rock type descriptions

The Oxford Clay Formation is a nearly uniform succession of silicate mudstone which is grey, variably silty, with sporadic beds of argillaceous limestone nodules. Over most of the outcrop it comprises a tripartite succession of an upper part (Weymouth Member) which is mainly pale grey, calcareous mudstone; a middle part (Stewartby Member) which is mainly pale to medium grey mudstone with subordinate beds of silty shell debris-rich mudstone and a lower part (Peterborough Member) which is largely a brownish grey, fissile, organic-rich mudstone (Wright and Cox, 2001).

In the Hampshire 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.

4.2.1.7 GREAT OOLITE GROUP — LSSR

Distribution and thickness

The Great Oolite Group crops out along the western part of the district in a broadly north–south trending belt that extends from the Dorset coast toward Sherborne. The outcrop belt is irregular with offsets created by west–east-trending faults and erosion of the succession beneath the Early Cretaceous unconformity in the area of the North Dorset Downs. From the area of outcrop, the Great Oolite Group dips toward the east, with the top reaching a depth of around 1400 m below OD in east Hampshire. The Great Oolite Group occurs within the depth range of interest within a broad north–south belt broadly bounded by Sherborne in the west and Salisbury in the east.

The Great Oolite Group reaches 300 m thick in south Dorset between Weymouth and Swanage and in the area south of Blandford Forum. Separating these two regions of thick Great Oolite Group is an area around Dorchester where it has been partially removed by erosion beneath the Early Cretaceous unconformity (Bristow et al., 1990). Over the remainder of the Hampshire region the Great Oolite Group is typically around 100 to 200 m thick (Whittaker, 1985).

Principal information sources

In addition to information derived from the outcrop along the south and west of the Hampshire region (Cox and Sumbler, 2002) the Great Oolite Group is proven in a large number of deep hydrocarbon exploration boreholes within the depth range of interest, including the numerous boreholes around the Wytch Farm oilfield – West Stafford 1, Martinstown 1, Mappowder 1, Fifehead Magdalen 1, Shrewton 1 (Whittaker, 1980) and Urchfont 1. Borehole geophysics and cuttings provide good control on the stratigraphy. The Great Oolite Group was almost fully cored in the Winterborne Kingston 1 Borehole which provides a detailed description of the stratigraphy (Rhys et al., 1982).

Rock type descriptions

The Great Oolite Group within the region consists of a number of interbedded limestones and mudstones (Figure 12). The main mudstone intervals are the Frome Clay and the Fuller’s Earth formations and are best developed in the thicker Great Oolite Group successions of south Dorset (Rhys et al., 1982). Toward the north of the region, approaching the Cotswold–Weald shelf (Figure 11) the Great Oolite Group thins and mudstones are progressively replaced by thicker amalgamated predominantly ooidal limestones (Cox and Sumbler, 2002).

The Frome Clay Formation is 60 m thick in the Winterborne Kingston Borehole and consists of medium to dark grey mudstones. The mudstones are mostly calcareous apart from a thin, black, non-calcareous unit at the base overlying the limestones of the Wattonensis Beds Member (Rhys et al., 1982).

The Fuller's Earth Formation consists of grey, calcareous mudstone with interbedded limestone becoming more common toward the top. In the Winterborne Kingston borehole the formation is 113 m thick (Rhys et al., 1982).

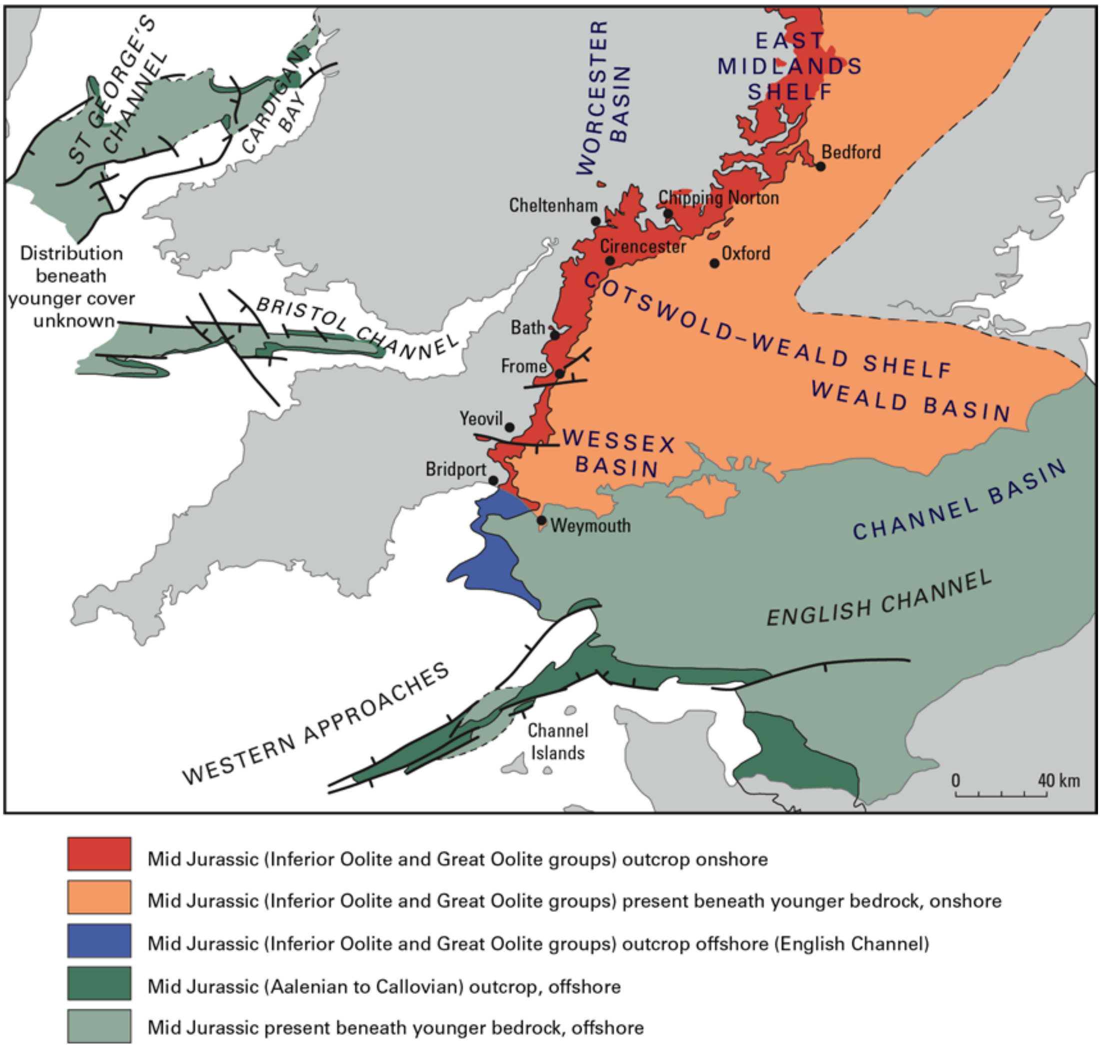


Figure 11 Distribution of Mid Jurassic strata in southern Britain including adjacent offshore areas (Barron et al., 2012). British Geological Survey © UKRI 2018.

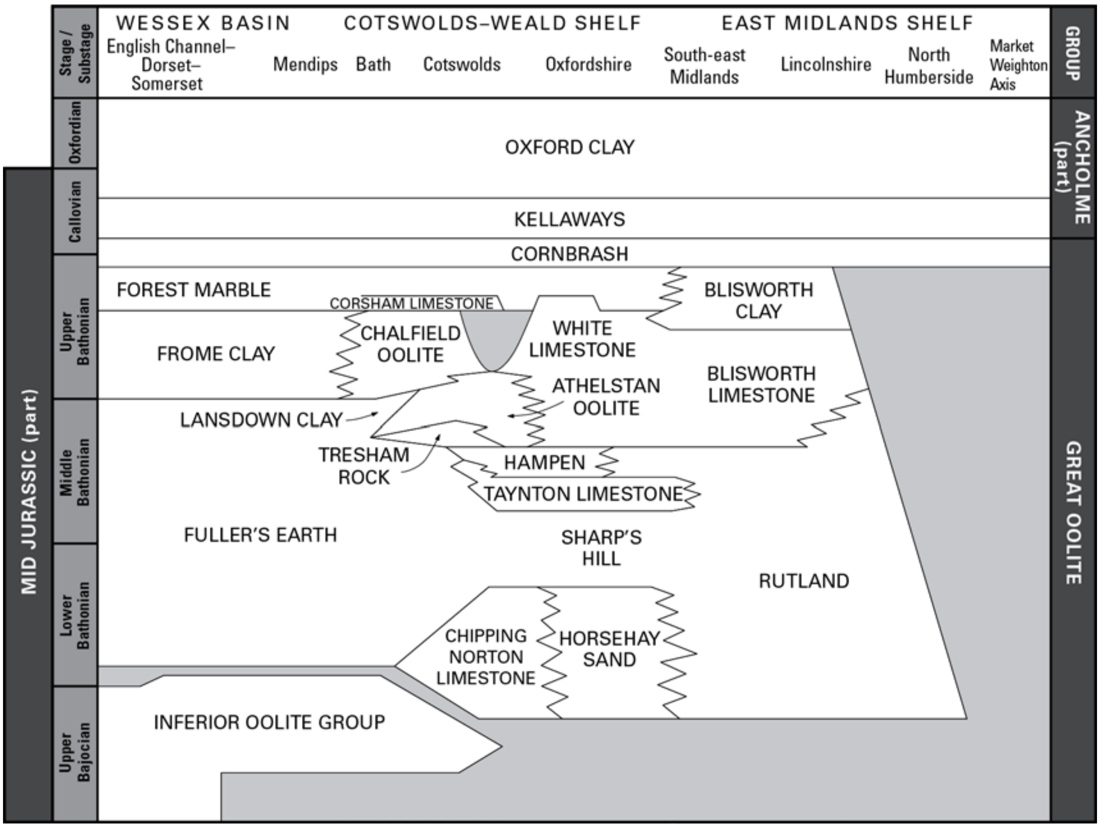


Figure 12 Stratigraphy of the Great Oolite Group in the Wessex Basin with correlative units on the Cotswolds–Weald shelf and East Midlands shelf (Cox and Sumbler, 2002).

4.2.1.8 LIAS GROUP — LSSR

Distribution and thickness

The Lias Group is traditionally divided into three informal parts, the Lower, Middle and Upper Lias. The Lower and Middle Lias comprise marine clays and limestones, whilst the Upper Lias is predominantly shallow marine sands and limestones (Barton et al., 2011; Andrews, 2014; Hamblin, 1992). The Lias Group is present at outcrop in a broadly north–south belt which passes through Bridport and Yeovil in the west of the region. From here it dips toward the east reaching depths of around 1800 m below OD in east Hampshire (Whittaker, 1985). The mudstone-rich Lower and Middle Lias occur within the depth range of interest in a north–south-trending belt that passes through Dorchester, Sherborne and Warminster and mostly lies to the east of Yeovil and to the west of Fordingbridge. To the south of Blandford Forum, the downfaulted Winterborne–Kingston trough (Figure 5) (Rhys et al., 1982), causes a marked westward deflection in the area where the Lias Group occurs within the depth range of interest.

The Lower and Middle Lias reach their maximum thickness of 300–450 m in areas of south Dorset around Weymouth, Dorchester and south of Blandford Forum. Throughout the remainder of the region the Lower and Middle Lias is mostly less than 200 m thick, apart from local thickening in certain areas such as south of Devizes and Andover to the north of the Hampshire–Dieppe high (Figure 6) (Whittaker, 1985; Duff and Kenyon-Smith, 1992).

Principal information sources

The Lias Group in the depth range of interest is proven in a number of deep hydrocarbon exploration boreholes including Chickerell 1, Martinstown 1, Nettlecombe 1, Seaborough 1, Ryme Intrinseca 1, Fifehead Magdalen 1 and Norton Ferris 1. The Lias Group was partially cored in the Winterborne Kingston Borehole (Figure 13) which provides a detailed description of selected intervals (Rhys et al., 1982). At outcrop, the group is well known from type sections along the Jurassic Coast of south Dorset (Cox et al., 1999).

Rock type descriptions

Five distinct formations are recognised in the Lias Group of the Hampshire area (Figure 10) (Cox et al., 1999) described from youngest to oldest. The formations are lithologically distinct and can be readily identified on geophysical logs (Whittaker et al., 1985).

- The Bridport Sands Formation are typically around 100 m thick and comprise an alternation of grey, friable sands with hard calcareous cemented sandstone beds.
- The Beacon Limestone Formation is a thin ferruginous limestone that occurs at the base of the Bridport Sands Formation.
- The Dyrham Formation consists of pale to dark grey and greenish grey, silty and sandy mudstone, with interbeds of silt or very fine-grained sand (locally muddy or silty). There are impersistent beds of ferruginous limestone (some ooidal) and sandstone, which tend to occur at the top of sedimentary cycles and sporadic large cementstone nodules.
- The Charmouth Mudstone Formation consists of dark grey laminated shales, and dark, pale and bluish grey mudstones. Locally there are concretionary and tabular limestone beds, argillaceous limestone and phosphatic or ironstone (sideritic mudstone) nodules. Organic-rich paper shales occur at some levels.
- The Blue Lias Formation consists of thinly interbedded limestone (laminated, nodular, or massive and persistent) and calcareous mudstone or siltstone (locally laminated). Individual limestones are typically 0.1–0.3 m thick.
-

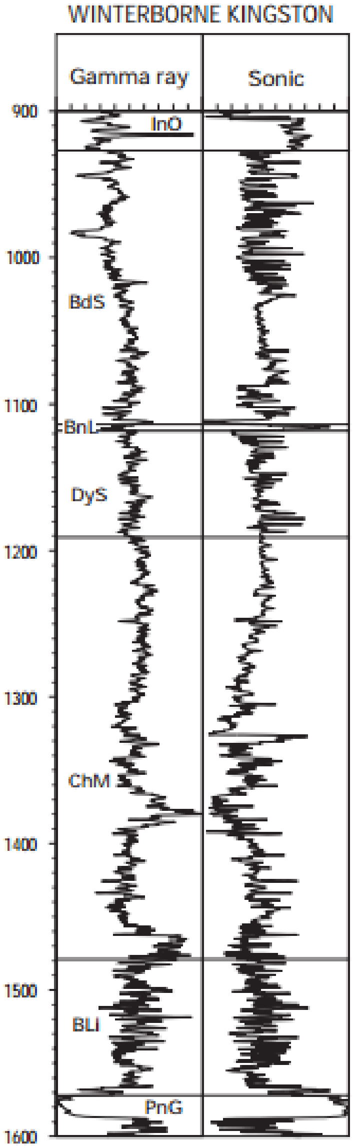


Figure 13 Stratigraphy of the Lias Group in the Winterborne Kingston Borehole (Cox et al., 1999). See Figure 3 for borehole location. The Lias Group subdivisions are BdS = Bridport Sands Formation; Bnl=Beacon Limestone Formation; Dys=Dyrham Formation; ChM=Charmouth Mudstone Formation; BLI=Blue Lias Formation. The Lias Group is underlain by the Penarth Group (PnG) and overlain by the Inferior Oolite Formation (InO). British Geological Survey © UKRI 2018.

4.2.1.9 Undivided Mercia Mudstone and Penarth groups — LSSR and EVAP

Distribution and thickness

The Mercia Mudstone Group and overlying Penarth Group are modelled undivided in NGS3D.

The Mercia Mudstone Group occurs across all of the Hampshire region entirely concealed beneath younger formations with the exception of a small (2 km^2) area of outcrop 10 km north of Yeovil in Somerset. The depth of the top of the Mercia Mudstone Group generally increases from west to east so that it occurs within the depth range of interest in a belt extending from Bridport in south Dorset, through Yeovil and Warminster. In east Hampshire, the top of the formation is some 2 km below the surface (Figure 14).

The Late Triassic Penarth Group (previously known as the Rhaetic Beds) represents an upwards transition from the underlying Mercia Mudstone Group and is modelled as part of the Mercia Mudstone Group in NGS3D. The Penarth Group was deposited in a shallow marine setting subject to episodic lagoonal and estuarinal conditions. The Penarth Group occurs across the Hampshire region entirely concealed beneath younger formations. The depth of the top of the Penarth Group generally increases from west to east so that it occurs within the depth range of interest in a belt extending from Bridport in south Dorset, through Yeovil and Warminster. In east Hampshire, the top of the formation is some 2 km below the surface. The Penarth Group has a relatively uniform thickness of 20–30 m across the Hampshire region

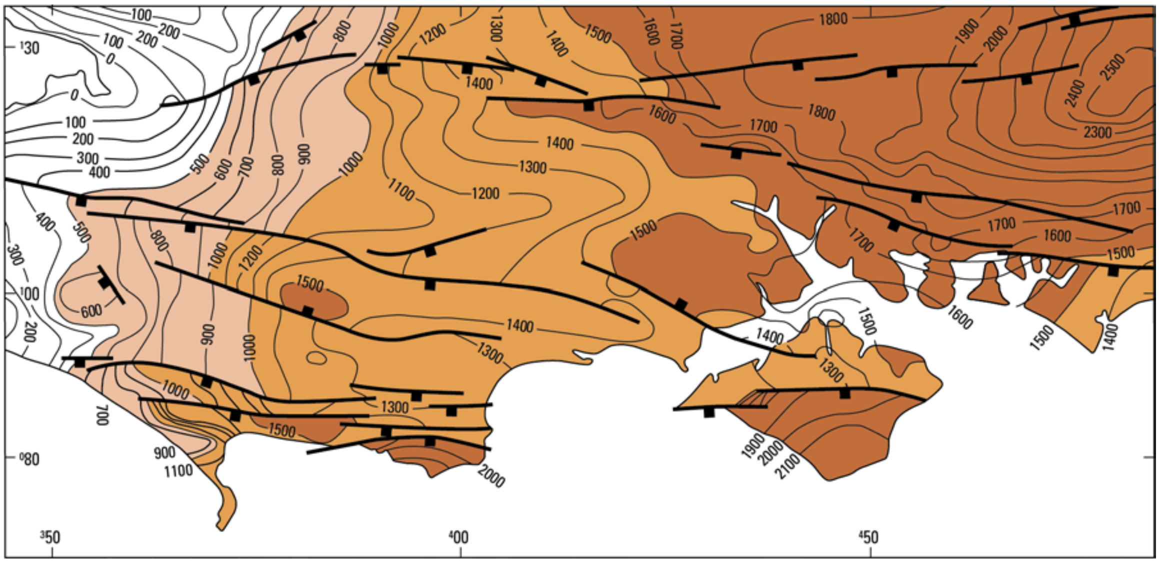


Figure 14 Contour map (depths are in metres below sea level) of top of the Mercia Mudstone Group in the Hampshire region (Whittaker, 1985). British Geological Survey © UKRI 2018.

The Mercia Mudstone Group ranges up to 950 m thick. The thickest deposits occur in south Dorset in the area to the south of Yeovil, Blandford Forum and Bournemouth where it is typically 500–900 m thick (Bristow et al., 1990). Across Wiltshire, Hampshire and north-east Dorset the formation thins rapidly and is generally 100–300 m thick (Whittaker, 1985).

Principal information sources

Within the depth range of interest, the Mercia Mudstone Group is proved in a number of deep exploration boreholes including Nettlecombe 1, Marshwood 1, Seaborough 1, Ryme Intrinseca 1, Fifehead Magdalen 1 and Norton Ferris 1. Short sections of the Mercia Mudstone Group were cored in the Winterborne Kingston Borehole (Rhys et al., 1982).

The Penarth Group is proved in a number of deep boreholes including Nettlecombe 1, Marshwood 1, Seaborough 1, Ryme Intrinseca 1, Fifehead Magdalen 1 and Norton Ferris 1. Short sections were cored in the Winterborne Kingston Borehole (Rhys et al., 1982).

Rock type descriptions

The Mercia Mudstone Group comprises reddish brown mudstone with minor sandstone beds and localised, but locally thick, intervals of evaporites (Howard et al., 2008). The mudstones, typically structureless with a distinct conchoidal fracture, contain common gypsum/anhydrite nodules up to 10 cm in diameter and more rarely as veins. The upper part of the sequence, the Blue Anchor Formation consists of interbedded green-grey and red-brown mudstones interbedded with limestones (Rhys et al., 1982).

Within the Mercia Mudstone Group, evaporites are primarily located in south Dorset where the Dorset Halite Member is sandwiched between lower and upper intervals of mudstone represented by the Sidmouth Mudstone Formation and the Branscombe Mudstone Formation (Figure 15). Only in certain locations such as around the Marshwood 1 and Nettlecombe 1 boreholes in south Dorset do the halites occur within the depth range of interest (Figure 15).

The Penarth Group consists of limestones, mudstones and sandstones (Rhys et al., 1982). Three main units are recognised: an upper unit of massive limestone (Langport Member of the Lilstock Formation), a middle unit of pale grey calcareous mudstone (Cotham Member of the Lilstock Formation) and a lower unit dominated by dark grey laminated mudstone passing downwards into sandstone (Westbury Formation) (Rhys et al., 1982).

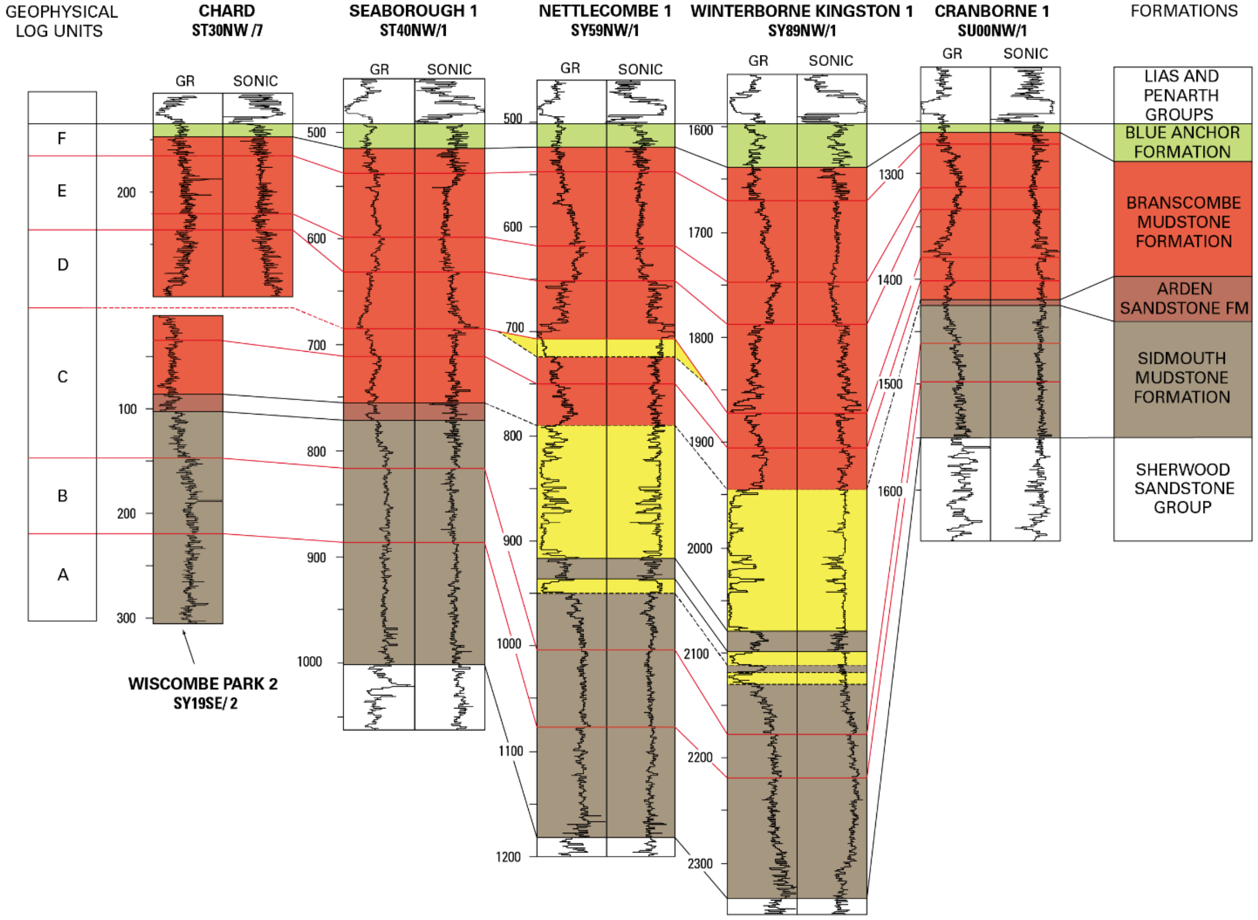


Figure 15 Log correlation showing the stratigraphical position of thick evaporites (in yellow) in the Mercia Mudstone Group (Howard et al., 2008). Log depths in metres below rotary table elevation. See Figure 3 for borehole locations in the Hampshire region with the exception of the Chard borehole which is located in the adjacent South-west England region. British Geological Survey © UKRI 2018.

4.2.1.9.1 UNDIVIDED PERMIAN ROCKS — LSSR

Distribution and thickness

In the Hampshire region, the Permian Aylesbeare Mudstone Group has a patchy subsurface distribution, infilling irregular topographical lows and basins on the Variscan unconformity, generally at depths in excess of 1 km from the surface (Whittaker, 1985). The Aylesbeare Mudstone Group only occurs within the depth range of interest in south Dorset around Bridport, where approximately 328 m were proved in the Marshwood 1 Borehole. From here the Permian deposits generally dip to the east toward their eastern limit of deposition around Bournemouth Bay. The thickest deposits occur around Poole Harbour and Bridport (Bristow et al., 1990).

Principal information sources

The distribution and thickness of the Aylesbeare Mudstone Group is known from a number of hydrocarbon exploration boreholes including Marshwood 1, Nettlecombe 1 and Wytch Farm X14 in south Dorset. Borehole (drill) cuttings and geophysical logs provide information on the lithology of the group. In central and northern parts of the region such as around Wincanton and Shaftesbury, the presence of the group is inferred from seismic reflection surveys (Bristow et al., 1999). Short sections of the Aylesbeare Mudstone Group were cored in the Winterborne Kingston borehole (Rhys et al., 1982).

Rock type descriptions

In south Dorset, the Aylesbeare Mudstone Group typically comprises three main parts (Bristow et al., 1990). At the top are brown blocky mudstones which are interbedded with sandstone and siltstone giving a typically serrated response on gamma-ray logs (Bristow et al., 1990). This is underlain by a sequence of fining-up conglomerates interbedded with sandstones. Below this are brick-red, blocky mudstones which are locally silty and sandy and often overlie a basal breccia developed on the Variscan unconformity.

4.2.2 Basement rocks

4.2.2.1 UNDIVIDED LATE DEVONIAN — HSR

Distribution and thickness

Higher strength, pre-Permian basement rocks are entirely concealed in the Hampshire region typically occurring at depths of 0.5 to 4.0 km below sea level (Chadwick, 2005). The shallowest pre-Permian rocks occur in the north-western part of the region on structural highs that are contiguous with the exposed Palaeozoic rocks of the Quantock and Mendip Hills (Bristow et al., 1995), extending into the Bristol and Gloucester district region, where they are modelled as Devonian rocks (undivided). Other shallow areas of basement occur in the north-eastern part of the region, where they flank the London platform, and under the northern half of the Isle of Wight which is part of the Hampshire–Dieppe high (Chadwick, 2005). Pre-Permian (Late Devonian) higher strength rocks, however, only occur within the depth range of interest within a narrow (15 km) belt that extends from Yeovil towards Trowbridge along the north-west periphery of the region.

Principal information sources

Pre-Permian higher strength rocks are proven in a small number of deep hydrocarbon exploration boreholes including Bruton 1, Norton Ferris 1 and Fifehead Magdalen 1 (Bristow et al., 1995; 1999). The structure is inferred from deep seismic refraction profiling, together with gravity and magnetic potential field data (Chadwick et al., 2005; Bristow et al., 1999; Andrews, 2014; Chadwick et al., 1983). The structure of the pre-Permian basement is complex, having been folded and thrusted by northward-directed Variscan compression and most interpretations carry a large uncertainty (Chadwick et al., 1983).

Rock type descriptions

The area between Yeovil and Wincanton lies to the south of the belt of Carboniferous limestones and comprises cleaved Devonian mudstones, sandstones and subordinate limestones transitional between continental and marine types (Bristow et al., 1995). To the south of Yeovil are Devonian phyllites and slates which were proven in the Ryme Intrinseca 1 Borehole below the depth range of interest.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in Hampshire region and shows their surface extent on a map (Figure 16). Many of the structures are well known and are identified in the BGS regional guides and memoirs. As described in the guidance (RWM, 2016a), they are relevant to safety in two ways: they may provide effective limits to any rock volume being considered for siting a GDF, and they have an impact on the uniformity and predictability of rocks and groundwater at a scale of relevance to a GDF.

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

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

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

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

Much of the Hampshire region and the adjacent Wealden district region are underlain by the Variscan fold belt, affecting older, late Palaeozoic rocks, and bounded in the extreme north-west by the Variscan foreland (VF), forming part of the Caledonian basement beneath these areas and comprising Precambrian rocks of the London-Brabant Massif and the main subdivisions of the Midlands massif or microcraton to the north-west and in the north-east of Kent, the Anglo-Brabant Massif (Smith et al., 2005; Lee et al., 1990; Lee et al., 1991; Chadwick et al., 1989). For the purposes of this report it is useful to refer to groups of strata as follows:

- younger cover (Permo-Triassic to Palaeogene)
- older cover ('foreland' Carboniferous in the far north of the region, north of the Variscan Frontal Thrust zone)
- Variscan basement (deformed Precambrian to Carboniferous, south of the Variscan Frontal Thrust zone)
- Caledonian basement (Precambrian to early Palaeozoic rocks, north of the Variscan Frontal Thrust zone)

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 (the Variscan Frontal, Pewsey, Wardour and Portland–Wight thrusts, shown on Figure 6). A number of north-west-oriented wrench faults have also been tentatively identified in the basement (e.g. the Watchet–Cothelstone Hatch fault). 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 structures recognised across the region and affecting the younger (Mesozoic and Cenozoic) rocks were formed during subsequent 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 the majority of the region, that the true subsurface nature and ultimate origin of the Cenozoic fold structures has 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 (down 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 down-to-south, shortcut, normal faults were initiated, facilitating the collapse of the hanging-wall block to form a series of faulted intrabasinal highs and graben/half-graben within which smaller sedimentary sub-basins developed. Within the main Wessex Basin, the most notable sub-basins are the Mere and Portland–Wight basins, which are separated by the Hampshire–Dieppe high (also known as the Cranborne–Fordingbridge high) (Figure 6). These structures strongly influenced and controlled the distribution of the 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. These structures were still influencing deposition into the Late Cretaceous. Episodes of fault movement were interspersed with periods when subsidence took place more generally (post-rift subsidence), and sediments thickened more evenly towards the depocentres and even over the intervening highs. 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.

Deposition in Palaeocene to Oligocene times was prior to and contemporaneous with, a compression and inversion tectonic regime during Late Eocene to Miocene Alpine and Pyrenean orogenic events (Lake and Karner, 1987; Chadwick, 1993; Chadwick and Evans, 2005; Parrish et al., 2018). 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 normal 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 inversion along faults, can produce markedly different juxtapositions of rock.

5.3 MAJOR FAULTS

Across the region, discrete, generally east–west trending structural zones of folding and faulting are identified, separated by wider less deformed areas. Five main structural zones are recognised:

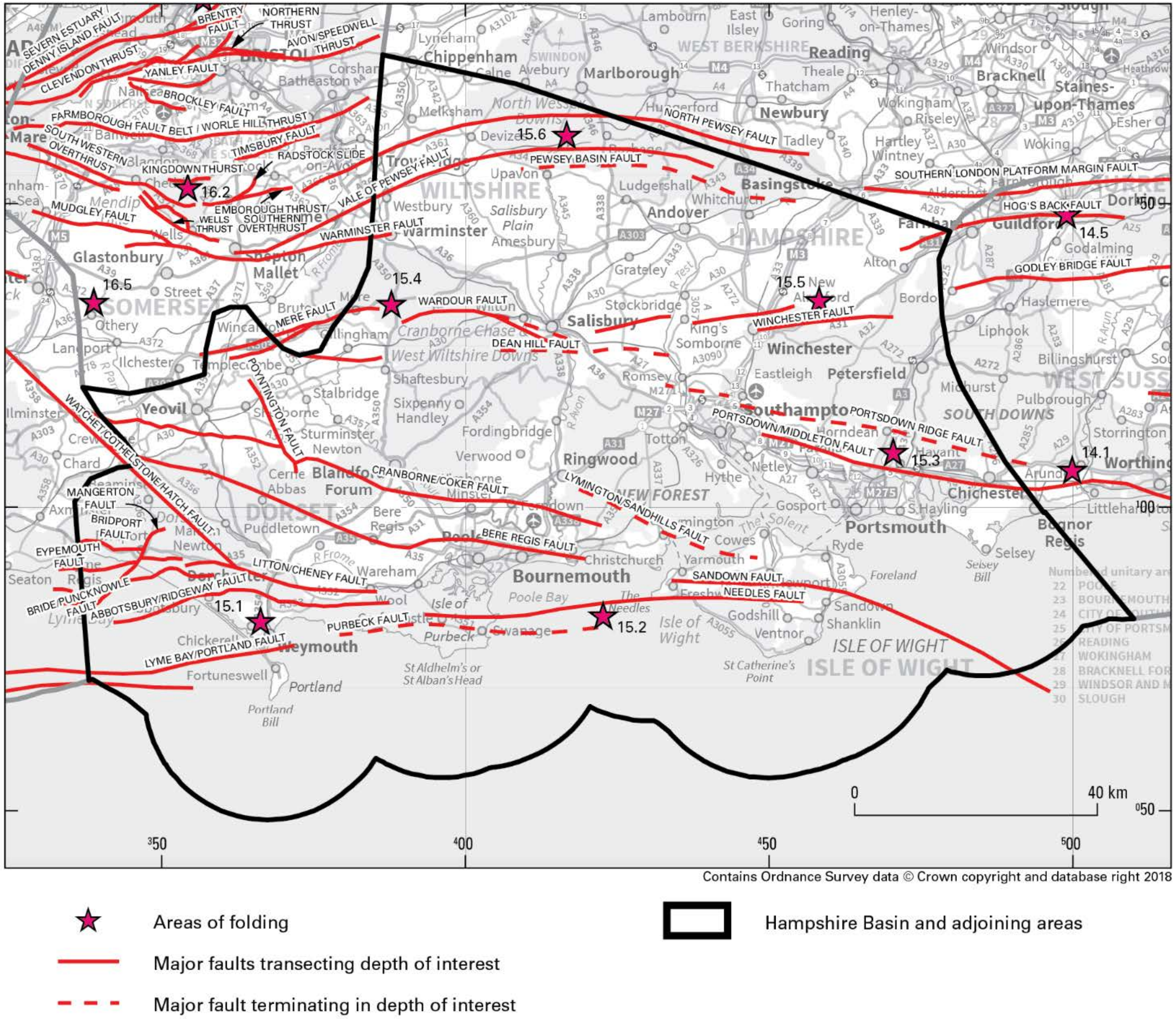
- an arcuate northern zone between Frome and Trowbridge in the west to Basingstoke in the east: Vale of Pewsey, Pewsey basin, North Pewsey faults
- an arcuate central zone between Templecombe and Mere in the west to Chichester in the east: Mere, Wardour, Portsdown Ridge and Portsdown–Middleton faults
- an east–west trending zone between Salisbury in the west to east of Winchester: Dean Hill and Winchester faults
- a north-west to south-east-trending structure between Ilminster in the north-west and Parkhurst on the Isle of Wight in the south-east: Cranborne–Coker, Bere Regis and Lymington–Sandhill faults
- an east–west trending zone in the south of the region between Lyme Regis in the west through Purbeck and the Isle of Wight into the English Channel: Bridport, Eypemouth, Litton–Cheney, Abbotsbury–Ridgeway, Lyme Bay–Portland, Purbeck, Needles and Sandown faults

They are related to and reflect pre-Permian basement structures, which may extend offshore and across the English Channel. The influence of structural control from the underlying basement and frequently, a comparable displacement history, reflect the behaviour of similarly orientated fault planes to extension or compression in the contemporary regional stress field.

In the following description, the major faults are described in terms of a set of faults with a dominant orientation, usually reflecting the influence of structural control from the underlying pre-Permian basement and frequently, a comparable displacement history. The location of individual fold structures (anticlines, periclines, monoclines, synclines) referred to in this section are not shown on maps; the reader is to assume that named fold structures follow the line of the fault with the corresponding name . The major fault zones are predominantly down-to-south normal faults, such as the Cranborne–Coker, Purbeck, Needles and Sandown faults. They do however, also include antithetic, down-to-north faults such as the Bere Regis Fault, which together form narrow generally east–west graben (e.g. the Winterborne–Kingston trough (Figure 5)). As this region is occupied by younger cover sequences at outcrop, folding is usually related to inversion of these strata and is localised to the major basin-controlling normal fault zones, which suffered such reversal. Given the main faults dip to the south, the inversion fold structures are typically linear in form, verging (facing) northwards and often monoclinal in nature, with steep to overturned northern limbs. Typical of this type of structure are the Abbotsbury–Ridgeway, Portland–Wight and Wardour–Portsdown structures, with the associated folding being typified by the Vale of Wardour Anticline and the Sandown, Needles and Purbeck monoclines. These structures may also have steep, southwards-dipping reverse faults, or thrusts, associated with the steepened, northern limb. (e.g. Chadwick, 1986; 1993; Chadwick and Evans, 2005; Evans et al., 2011; Barton et al., 2011). When traced laterally to the fault tips, where displacement was less, anticlinal structures are generally developed, examples being seen in association with the Mere Fault (Barton et al., 1998; Chadwick and Evans, 2005). Other inversion structures present are anticlines (or periclines) in the hanging-wall block successions to the main basin-bounding faults, including those associated with the Abbotsbury–Ridgeway fault: the Poxwell, Sutton Poyntz and Chaldon Herring anticlines.

The main faults developed within the depth range of interest have arcuate east–west trends, being controlled by underlying, similarly trending, southerly dipping Variscan thrusts in the pre-Permian basement. Beneath the region, two thrusts are identified from seismic refection data: the Wardour and Variscan Frontal thrusts, formed in latest Carboniferous times and postdating strata of Westphalian age. The Wardour Thrust (and its westerly continuation the Somerton Thrust and others described in more detail in the adjoining South-west England region and the Bristol and Gloucester region, 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, which lies along strike from the outcrop of basement rocks in the Mendip Hills.

In addition to the main east–west trending Variscan thrusts in the pre-Permian basement, a system of widely spaced, subvertical, dextral, north-westerly trending, wrench or transcurrent faults formed contemporaneously with 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 (see adjoining regions companion reports). They also underwent re-activation and affected Permian and Mesozoic basin development, sediment thickness and distribution. The main such fault zones in the adjacent regions to the west are the Sticklepath–Lustleigh fault system (SLF) and the Watchet–Cothelstone–Hatch fault system, the latter extending into the western margins of the region and covered in greater detail in the South-west England region companion report. A number of other transcurrent faults are known in the Hampshire region, including the Mangerton and Poyntington faults.



Contains Ordnance Survey data © Crown copyright and database right 2018

Figure 16 Major faults and areas of folding in the Hampshire 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 Warminster, Vale of Pewsey, Pewsey basin, Southern London Platform Margin and Hog’s Back faults

Running across the north of the region, the Warminster, Vale of Pewsey, Pewsey Basin, Southern London Platform Margin and Hogs Back faults (Pewsey–London Platform faults) are a complex, mixed sense of throw, braided series of arcuate, predominantly east–west-trending, *en échelon*, down-to-south, Permian and Mesozoic syndepositional normal faults, with varying degrees of reversal. The faults mark the northern margin of Mesozoic Wessex and Weald extensional basin development and the southern limits of the London–Brabant massif. The fault zone extends over 165 km from Westbury in the west, eastwards through the northern areas of the region towards Basingstoke in the north-east. Hereabouts, the fault zone passes eastwards into the adjacent district region, where it extends through the Guildford area as the Hog’s Back structure, marking the northern limit of the Weald basin.

Within the Hampshire region, the Pewsey–London Platform faults comprise three main *en échelon*, down-to-south normal fault structures: the North Pewsey, Vale of Pewsey and Pewsey basin faults. These faults have up to 1000 m of net displacement, form the northern boundary of the Mesozoic Pewsey basin depocentre and define the northern limit of Mesozoic basin development in southern England. These major fault zones were controlled by the extensional reactivation of Variscan front thrusts within the basement and have variously suffered reversal of throw (inversion) during Alpine compression. They transect the depth range of interest.

Movement on the Pewsey faults led to southward thickening of Early Jurassic sediments into the Pewsey Basin. This thickening was less marked than in Permo-Triassic times, but the width of the Pewsey fault zone increased as new faults developed to the south. The London Platform faults, which form the easterly continuation of the Pewsey faults, might have been dormant in Permo-Triassic times, but by the Early Jurassic started to control development of the Weald basin (Chadwick, 1986; Whittaker, 1985). The faults are not associated with significant rollover development, appearing to have roughly planar geometries with deep detachments (Chadwick, 1986).

The North Pewsey Fault is the most northerly of the Pewsey faults, with a length of about 76 km and a net normal displacement in places of up to 1000 m. The Vale of Pewsey Fault has a length of over 83 km and a net normal displacement in places in excess of 1000 m. This is the main fault underlying the Pewsey Anticline. The Pewsey basin Fault to the south has a length of approximately 47 km and a net displacement in places of more than 600 m. These are very large faults with significant damage zones and as previously mentioned, current net displacements are a little misleading due to their subsequent partial reversal, with deeper levels retaining net normal displacement, but shallower levels showing net reverse displacement. The main strata affected in the depth range of interest are Jurassic and Early Cretaceous in age. At crop the Pewsey Anticline, about 20 km west-south-west of Newbury, is a related gentle, northerly verging inversion fold with steepening of its northern limb, with localised surface fault expression.

The down-to-north Warminster Fault extends into the north-west of the region as a southern antithetic structure to the Vale of Pewsey Fault. At least 25 km long, it is near vertical for much of its length with syndepositional movement during part of the Mesozoic. This movement appears to have ceased by the early Bajocian, as it did not affect Inferior Oolite Group deposition. The fault similarly suffered mild reactivation in compression during the Neogene (Alpine) compressional events, resulting in a net reverse throw at outcrop. Net normal displacement at depth may be over 620 m, whilst estimates at outcrop indicate variable downthrows to south and north of between 70 and 30 m, with the fault cutting the Grey Chalk subgroup in the Frome district.

The Southern London Platform Margin and Hog’s Back faults are described in the companion Wealden district report.

For more details see Chadwick et al. (1983); Chadwick (1986); Whittaker (1985); Lake and Karner (1987); Bristow et al. (1998; 1999) and Chadwick and Evans (2005).

5.3.2 Mere, Wardour, Dean Hill, Portsdown Ridge and Portsdown–Middleton faults

Running across the upper central parts of the region, the Mere, Wardour, Dean Hill, Portsdown–Middleton, Portsdown Ridge fault zone is a complex, mixed-sense-of-throw, braided series of predominantly east–west-trending, arcuate, down-to-south, *en échelon*, syndepositional normal faults, with varying amount of reversal. The fault zone extends over 100 km across the region, from near Mere in the west, eastwards towards Salisbury and then east-south-eastwards to north of Southampton and through Chichester in the far south-east. From there it extends further eastwards into the adjacent region, to reach the coast near Worthing from where it continues offshore into the English Channel. The faults, originating as down-to-south syndepositional normal faults in Permian times, and controlled by a major southerly dipping Variscan basement thrust (the Wardour Thrust), show the greatest normal displacement at depth and suffered reactivation in extension on a number of occasions.

The main fault zones are, from west to east, the Mere, Wardour, Dean Hill, Portsdown Ridge and Portsdown–Middleton faults. The Mere, Wardour and Dean Hill fault zones form the boundary between the Hampshire–Dieppe high and Mere basin (Figure 6), developed to the south, and the southern, updip part of the northerly tilted fault block, forming the Pewsey basin to the north. To the south-east the Portsdown Ridge and Portsdown–Middleton fault zones form the southern and south-western end of the main Weald basin depocentre and the northern margin of the Hampshire–Dieppe high and south-eastwards extension of the Mere basin. The Portsdown–Middleton Fault underlies the northern margin of the Portsdown inversion anticline.

The Mere, Wardour, Dean Hill, Portsdown–Middleton, Portsdown Ridge faults in general show variable but normal displacement of several hundreds of metres at depth. Changes in the thickness of the strata across the Portsdown and Middleton 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. However, the various fault segments have suffered differing degrees of reversal during Cenozoic (Alpine) compressional phases and locally show net reverse displacements at shallow depths and the development of a northerly verging inversion anticline. These are seen in the more easterly segments, which suffered the least erosion (and thus preserve the highest structural levels), including the Wardour Monocline, on the northern flank of the gentler Wardour Anticlinal uplift, and Portsdown Anticline, all Cenozoic inversion folds developed in the hanging-wall block to the south of the original down-to-south normal fault (zone). The anticlinal upfold of the hanging-wall sedimentary sequence is paralleled by the Bere Forest/Chichester Syncline (downfold) about 2 km to the north.

Based upon the Whittaker (1985) maps, in general, the Mere Fault zone has a length of about 68 km and a displacement in excess of up to 600 m. The western Mere segment shows a greater degree of erosion with a maximum apparent normal throw from UK3D of around 520 m, although this varies along strike, due to the degree of later reversal of throw during the Cenozoic (Alpine) inversion episode. The null point varies along the Mere Fault, being within the eroded Late Jurassic section in the west, within the outcropping Late Triassic section in the central (Zeals) segment and beneath the Gault Formation in the Wardour Monocline farther east.

The Dean Hill Fault to the south has a length of approximately 32 km and a normal displacement of up to 700 m. Continuing south-eastwards, the south-dipping Portsdown Ridge Fault has a length of about 51 km but its displacement is more variable, having suffered greater inversion such that reverse movement is seen at many stratigraphical levels along its length. To the south, the Portsdown–Middleton Fault has a length of about 80 km and a net displacement of up to 100–200 m, although this reflects Cenozoic inversion. It is associated with an inversion anticline: the Dean Hill Anticline, which is an asymmetric pericline with a shallow 1–2° dip on its the southern limb and a much steeper 8–12° dip on its northern limb. It plunges eastwards at around 1–2°.

The Mere–Wardour–Portsdown fault zone thus transects the depth range interest, but because of the varying degrees of extension and subsequent reversal, the various *en échelon* fault zones show varying net displacements along their lengths. Nevertheless, they are major fault structures with important inversion anticlines developed and are likely to have considerable damage zones associated with them.

For more details see Hopson (1999); Mansy et al. (2003); Chadwick (1993); Chadwick and Evans (2005); Chadwick et al. (1983); Bristow and Donovan (1999); Barton et al. (1998); Booth et al. (2008) and Lake and Karner (1987).

5.3.3 Winchester fault zone

The Winchester fault zone is a relatively poorly understood, mixed-sense-of-throw, complex-braided, dominantly east–west-trending, down-to-south fault system. It splays off east-north-east from the Mere–Wardour fault zone just to the east of Salisbury and north of the Dean Hill Fault and extends eastwards as a series of three *en échelon* faults, the easternmost being the Winchester Fault, to near the eastern edge of the region and may extend into the Godley Bridge Fault in the adjacent region. The fault zone has a length of almost 50 km and at its greatest, a net displacement of 100–200 m and is associated with a series of *en échelon* inversion anticlines, the largest of which is the Winchester–Meon–Harting Combe structure and which passes westwards into the Winchester Anticline, which is *en échelon* to the Dean Hill Anticline of the Mere–Wardour–Portsdown fault zone. To the north and *en échelon* is the Stockbridge Anticline. In general, the small anticlinal structures have steeper dips on their northern limbs.

For more details, see Osborne White (1912); Booth et al. (2008); Farrant et al. (2011). This structure influenced Late Cretaceous sedimentation.

5.3.4 Cranborne–Coker and Bere Regis faults

Running across the southern central parts of the region, the Cranborne–Coker Fault is a complex braided, dominantly east–west trending, down-to-south series of normal faults. Overall it extends from the western margin of the region some 90 km eastwards to around New Milton, north-east of Christchurch in the east. The fault possibly extends further south-eastwards to merge with the eastern reaches of the Purbeck–Wight disturbance and defining the southern margin of the Hampshire–Dieppe high. The Cranborne–Coker Fault is the northern boundary to a prominent local Permo-Triassic graben, the Winterborne–Kingston trough (Figure 5), which is bounded to the south by a northerly dipping, down-to-north, antithetic normal fault: the Bere Regis Fault. The faults lie largely concealed beneath Cretaceous rocks and originated during periods of Permian to Mesozoic crustal extension and transect the depth range of interest, between 200 and 1000 m below NGS datum.

The Cranborne–Coker Fault passes westwards within the region to merge with the north-west to south-east-trending Watchet–Cothelstone–Hatch fault system. The Cranborne–Coker Fault extends over at least 73 km eastwards from near Holnest in the west to around 10 km west of Lymington on the Solent, defining the northern boundary of a Permian–Mesozoic depocentre (the Dorset basin) and the southern boundary of the Hampshire–Dieppe high. These faults do not appear to have suffered much later reversal of movement during the Cenozoic (Alpine) inversion episode.

The Bere Regis Fault is a slightly arcuate, generally east–west-trending, down-to-north normal fault defining the southern margin of the restricted Winterborne Kingston trough. It extends from around Holywell approximately 65 km eastwards to around Christchurch on the coast of Bournemouth Bay. It has a normal displacement of at least 645 m along its length, with little later apparent reversal of movement during the Alpine events. The Bere Regis Fault is associated with extensional rollover in its hanging-wall block, which is indicative of a listric fault geometry and perhaps a relatively shallow detachment (Chadwick, 1986).

Both the Cranborne–Coker and Bere Regis faults transect the depth range of interest. Displacements on the faults are greatest at depth (up to 700 m), often deeper than the depth range of interest, lessening to only 100–200 m at shallower depths within the depth range of interest. The faults do not appear to significantly offset the Early Cretaceous unconformity or younger surfaces: the Early Cretaceous surface dips eastwards along the length of the fault from near crop in the west to about 900 m depth in the east.

For more details see Barton et al. (2011); Bristow et al. (1991); Bristow (1995); Chadwick (1986), and Wilson (1958).

5.3.5 Bridport, Eypemouth, Litton–Cheney, Abbotsbury–Ridgeway, Lyme Bay–Portland, Purbeck, Needles and Sandown faults

Running across the southern parts of the region and into the English Channel, the Bridport, Eypemouth, Litton–Cheney, Lyme Bay–Portland, Abbotsbury–Ridgeway, Purbeck, Needles and Sandown faults represent a complex, mixed sense of throw, braided series of predominantly east–west-trending, arcuate, *en échelon*, down-to-south, syndepositional normal faults, which have suffered degrees of reversal. They originated during periods of Permian to Mesozoic crustal extension and the majority of the faults subsequently suffered reversal of movement during Cenozoic Alpine compressional events. A number of the faults show reverse faulting developed in strata at shallower levels and all have major northward-verging inversion anticline structures, with steepened northern limbs, developed in sequences of the hanging-wall block. Maximum normal throws are preserved at deepest levels, often deeper than the 1000 m being considered, but will be variable along strike, due to the degree of later reversal of throw during the Cenozoic (Alpine) inversion episode. Consequently, displacement of the stratigraphical units will be variable along strike. These structures will transect the depth range of interest and, due to their nature and structural evolution, separate important structural highs and depositional lows to the north and south respectively.

The main named faults include (from north-west to south-east) are the Bridport, Eypemouth, Litton-Cheney, Abbotsbury–Ridgeway, Lyme Bay–Portland, Purbeck, Needles and Sandown faults, the latter three *en échelon* faults forming the Purbeck–Wight disturbance, a major inversion structure extending almost 100 km across southern England from offshore in Weymouth Bay in the west, eastwards and onshore around Lulworth Cove to near Swanage (as the main Purbeck Fault) and across Bournemouth Bay onto the Isle of Wight (as the Needles Fault), passing eastwards into the Sandown Fault. From the east coast of the Isle of Wight, it is traced south-eastwards offshore and across the English Channel into France as the Wight–Bray Fault (also referred to as the Bembridge–St Valery line (Hawkes et al., 1998)). The Purbeck disturbance may also extend west from the Isle of Portland into Lyme Bay as the Lyme Bay–Portland Fault. The main eastern fault segments, south of Poole Harbour and on the Isle of Wight, separate two main components of the Wessex Basin, the Hampshire–Dieppe high to the north and the Portland–Wight basin to the south, and dominated the distribution of Triassic and Jurassic strata across that area.

The Purbeck Fault has a length of about 45 km and at its greatest, a net normal displacement in excess of 400 m. The Needles Fault has a length of around 60 km and at its greatest, a net normal displacement of more than 1000 m at depth. The Sandown Fault has a length of approximately 65 km and a displacement similar to the Needles Fault. All three are very large faults with significant damage zones likely and as previously mentioned, displacements in the shallow sections are difficult to predict and a little misleading due to the reversal of movement. Cenozoic reversal can be estimated from the inversion structures, with for example, the Sandown Fault and monocline. To the north of the monocline the base of the Chalk Group lies at 983 m below sea level, whereas south of the monocline it lies close to sea level, giving a down-to-north reverse throw of about 1000 m (Chadwick and Evans, 2005). The surface expression of the Sandown Fault comes to crop within the Oligocene strata to the north of the main monoclonal structure.

The Purbeck–Wight disturbance comprises three important faults, each associated with a major northerly verging inversion monoclinal structure, from west to east these are the Purbeck, Brighstone and Sandown monoclines. The monoclines have steep to overturned northern limbs, with reverse faulting of the Chalk and Cenozoic strata seen on seismic reflection data and now recognised at crop (Chadwick and Evans, 2005; Evans et al., 2011). *En échelon* and to the north of the western parts of the Purbeck–Wight disturbance is the arcuate Abbotsbury–Ridgeway fault zone, extending over 45 km from east of Chaldon Herring, westwards to Abbotsbury and offshore into Lyme Bay west of Chesil Beach. The fault is usually traced along the northern limbs of the inversion folds: the Sutton-Poyntz, Poxwell and Chaldon Herring periclines. The styles of deformation (both folding and faulting) are different to those of the main faults to the east in that there is evidence that the extensional phases evolved partly as a detached fault, soling out in the Triassic Dorset Halite Member, such that there was no hard linkage with the original underlying faults until extreme structural thinning of the salt beds had occurred. Currently, normal displacements of >500 m are known within the depth range of interest.

The Bridport–Eypemouth–Litton–Cheney faults, to the north of the Abbotsbury–Ridgeway fault zone, are traced over 45 km from the coast west of Bridport eastwards to just over 2 km south of Dorchester and onwards to around Wool, as a down-to-south, syndepositional normal fault. It lies largely concealed beneath Cretaceous rocks in the east, but segments of the fault zone are at crop in the west, where it comprises a number of down-to-south normal faults that are traced to the area around Burton Bradstock and Eypemouth on the Lyme Bay coast. Hereabouts, it is offset by the north-east to south-west-trending Mangerton Fault and appears to continue westwards as a down-to-south fault pair: the Bridport Fault to the north of Bridport (also associated with a smaller down-to-north antithetic fault forming a small graben) and the Eypemouth Fault on the coast. The Bridport–Eypemouth–Litton–Cheney fault zone does not appear to have suffered as much, if any, later reversal of movement during Cenozoic (Alpine) compression events. Current maximum net displacements along the fault zone are in the order of 350 m.

A number of inversion fold structures are associated with the fault zones, formed during Cenozoic (Alpine) compression. These include the broader Weymouth Anticline, and tighter, northerly verging Upwey Syncline, Sutton Poynz, Poxwell and Chaldon Herring periclines related to the Abbotsbury–Ridgeway fault zone and forming an *en échelon* series of folds extending for some 10 km. The Weymouth Anticline whilst in the hanging-wall block to the Abbotsbury–Ridgeway Fault, is also along strike from the western extension of the Purbeck disturbance and also has some thickening of the Triassic Dorset Halite Member in its core. It appears to owe some of it origin to halokinetic movements of the deeper buried massive Triassic halite beds.

For more details see Harvey and Stewart (1998); Wilson (1958); Chadwick and Evans (2005); Chadwick (1993); Barton et al. (2011); Peacock (2009); Lake and Karner (1987); Nowell (1995); Evans et al. (2011), and White (1921).

5.3.6 Lymington–Sandhills Fault

The generally west-north-west to east-south-east-trending Lymington–Sandhills Fault is a complex, concealed, mixed sense of throw, down-to-north fault with up to 660 m of normal displacement of Permian and Triassic strata, but extensions did not affect strata younger than the Inferior Oolite Group. It has a gentle arcuate/sinusoidal curvature, running onshore from around Ringwood in the west, approximately 35 km eastwards, through Lymington and across the Solent onto the Isle of Wight to north of Shalfleet, terminating around Parkhurst.

The fault suffered reactivation and some reversal during Cenozoic (Alpine) compression, with minor flexures forming a small group of inversion folds along its length. The most distinct fold is the gentle, south-east-trending anticline running through Wilverley Plain, Durns Town and Walhampton on the Solent coast. It is picked up again across the Solent on the Isle of Wight as the Porchfield Anticline, the formation of which involved little reverse faulting of the younger strata seen in the main down-to-south fault zones south of this structure. The fold structure would affect the depth range of interest, but faulting is likely to be deeper.

For more details see Chadwick and Evans (2005); Mortimore (2011), and Evans et al. (2011).

5.3.7 The Watchet–Cothelstone–Hatch fault system

The Watchet–Cothelstone–Hatch Fault comprises a system of north-west to south-east-trending strike-slip or transcurrent basement and cover faults, traceable for at least 40 km from the Bristol Channel, south-east into the Wessex Basin beneath the western margins of the Hampshire region. Traced south-eastwards, the Watchet–Cothelstone–Hatch Fault links with the east–west trending Cranborne–Coker Fault in the Ilminster area and is thought to extend south-eastwards as a dextral wrench fault with variable displacement to the south coast, separating structures like the east–west trending Litton–Cheney Fault and anticline from other *en échelon* faults and folds associated with the Isle of Purbeck Monocline.

The fault zone displays evidence of a complex movement history, involving early (Variscan) and late (possibly Cretaceous or Cenozoic) strike slip, separated by phases of normal extension. Cenozoic transpressional movements on the fault are evident and it is postulated that these led to the development of the Compton Valence Dome in the west of the region, perhaps also linked to a possible salt structure at depth. The Watchet–Cothelstone–Hatch Fault is described in more detail in the adjacent South-west England region companion report. However, within the region, the fault shows an overall down-to-south-west, normal sense of displacement at depth, but at shallower (higher) structural levels, there is more evidence of strike slip and reverse faulting.

For more details see Bristow et al. (1998); Miliorizos and Ruffell (1998), and Chadwick and Evans (2005).

5.3.8 Mangerton Fault, extending offshore into Lyme Bay

The Mangerton Fault is a steep north-north-east-trending, complex wrench or transcurrent fault zone mapped for about 8 km from Mangerton in Dorset southwards to Bridport on the south coast. Thereafter, it extends up to 7 km offshore into Lyme Bay. The Mangerton Fault appears to displace east–west-trending normal faults of the Bridport–Eypemouth–Litton–Cheney fault zone and is shown in UK3D as a steep, down-to-east reverse fault with a maximum apparent throw of approximately 500 m, but likely to be variable along strike. It thus transects the depth range of interest, but appears to affect only post-salt strata: the salt acting as a decollement horizon, isolating the pre- and post-salt sections (Harvey and Stewart, 1998).

For more details see Barton et al. (2011); Harvey and Stewart (1998), and Wilson (1958).

5.3.9 Poyntington Fault, Shaftesbury district

The north-north-west-trending Poyntington Fault, downthrown to the west, is an important structural element in the western part of the Shaftesbury district, the structural morphology of which is analogous with strike-slip faults elsewhere in the region and southern England. It is a braided fault zone, with many strands extending at least 20 km in a north-north-west to south-south-east direction from Corton Denham in the north, to the Cretaceous outcrop south of Shaftesbury District, where the displacement is transferred to a north-east to south-west-trending fault. The Poyntington Fault is primarily mapped as a wrench fault with net dextral offset, displacing the Cranborne–Coker Fault. The vertical displacement varies between 25 and 150 m. The fault belongs to the same group of structures cutting Devonian and Carboniferous rocks at outcrop farther to the west, such as the Sticklepath–Lustleigh and Watchet–Cothelstone faults, which show repeated reactivation and large displacements (see South-west England region companion report).

For more details see Bristow (1995); Chadwick and Evans (2005); Barton et al. (1998); Prodden (2005); Barton et al. (2011), and Wilson (1958).

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, 1992; Chadwick, 1993):

- Regional upwarps such as the Portland–Wight high and Weald Anticline (Figure 6) in the adjoining Wealden district region to the east, 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 which contain thick Early Cretaceous sequences.
- Long, roughly east–west-trending linear zones of en échelon inversion structures — these 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 the steepened limb.

For the purposes of this report, six major ‘foldbelts’ are recognised associated with the fault zones listed (see also Figure 16). Minor folds are found elsewhere but are of less significance.

- Abbotsbury–Ridgeway Fault, including the Weymouth Anticline and Poxwell, Sutton Poyntz and Chaldon Herring periclines
- Lyme Bay–Portland, Purbeck, Needles and Sandown faults, including the Sandown and Brighstone anticlines
- Portsdown–Middleton and Portsdown Ridge faults
- Mere and Wardour faults
- Dean Hill and Winchester faults, including the Winchester–Meon–Harting Combe structure
- Vale of Pewsey–Pewsey basin fault zone

5.5 UNCERTAINTY

A fault is recognised as being present because distinctive units of strata are offset by varying amounts relative to one another, both horizontally and vertically (throw), and in a normal or reverse sense. Surface evidence is based on geological mapping, where faults may be seen at crop, or their presence, attitude and location may be ascertained from mapping offset formational boundaries, for which the degree of confidence is in turn dependent upon the nature and degree of confidence in mapping those adjacent formations at crop. It is important to understand the nature of geological faults, and the uncertainties which attend their mapped position at the surface. Faults are planes of movement along which adjacent blocks of rock strata have moved relative to each other. They commonly consist of zones, perhaps up to several tens of metres wide, containing several to many fractures. The portrayal of such faults as a single line on the geological map is therefore a generalisation. Due to the thick cover of Cretaceous and younger stratigraphy across most of the region and the fact that these sediments postdate the major extensional tectonic phases, some of these faults are poorly mapped at surface. Consequently, areas where there is limited or no subsurface data carry the greatest degree of uncertainty in terms of the presence, location and nature of subsurface structures such as faults.

The presence of, and subsurface location, attitude and displacement of faults, may be evidenced by geophysical techniques. These techniques themselves carry varying degrees of confidence, depending on their varying degrees of sensitivity and thus resolution. Potential field (gravity and aeromagnetic) data are the least sensitive techniques on which to base interpretations, with structures identified and mapped tending to be larger scale. Seismic reflection data, generally acquired during hydrocarbon and coal exploration, provide greater resolution and thus permit more accurate identification, location and mapping of fault(s) and other structures in the subsurface.

Within the Hampshire region, the distribution of seismic lines is generally good except around Melksham, Sturminster Newton, between Warminster, Salisbury, Andover and Upavon, and in the east of the region between Wincanton, through Yeovil to Crewkerne. Where the seismic lines form a close grid, the recognition and location of subsurface faulting and folding carries higher confidence and is best constrained. 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 Hampshire region, the regional groundwater flow systems, and any units or structures that may lead to the effective separation of deep and shallow groundwater systems including evidence based on groundwater chemistry, salinity and age. It describes the hydrogeology of PRTIs (or their parent units), principal aquifers and other features, such as rock structure or anthropogenic features (including boreholes and mines), that may influence groundwater movement, and interactions between deep and shallow groundwater systems. It also includes a note on the presence or absence of thermal springs (where groundwater is >15º C) that may indicate links between deep and shallow groundwater systems.

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

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

6.2 GROUNDWATER SYSTEMS IN THE HAMPSHIRE REGION

There is some information related to groundwater in the depth range of interest, i.e. between 200 and 1000 m depth in the Hampshire region. However, the majority of the information is related to the relatively shallow groundwater system that is currently exploited for groundwater resources, typically to depths of <100 m but down to about 400 m. Since groundwater movement and chemical composition can vary significantly over short lateral and vertical distances, even in the depth range of interest, the level of uncertainty related to groundwater systems in the depth range of interest is high. It will be important to develop a detailed understanding of groundwater movement and chemistry and their implications for a safety case during any future siting process or site characterisation.

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The regional groundwater flow systems in the Hampshire region are conceptualised as being controlled by the broad distribution of geological units and the regional geological structure; the hydrogeological characteristics of those units; topography and the distribution of recharge; and other hydraulic boundary conditions, such as the coastline to the south of the region.

The GVS for the Hampshire region (Table 3) divides rock units into three age ranges: younger sedimentary rocks (Palaeogene to Permian), older sedimentary rocks and basement rocks. The stratigraphically lowest part of the younger sedimentary sequence, the Permian and Triassic sediments (apart from a small area of Penarth and Mercia Mudstone groups, around Eyewell), are not exposed in the region and are typically found at, or below, the depth of interest and receive no direct groundwater recharge. The overlying Lias Group outcrop area is found in the west of the region from the Isle of Portland, north through the Blackmoor Vale towards the Vale of Pewsey. The younger Jurassic, Cretaceous and Palaeogene sedimentary sequence generally crops out in an arc eastward around the northern flank of the asymmetrical Hampshire Basin Syncline and gently dip south-east, south or south-westward towards the centre of the syncline, re-emerging as deeply dipping units to the south of the syncline through Purbeck and the Isle of Wight (Section 3).

Within the younger Jurassic to Palaeogene sedimentary sequence, sediments below the Gault Formation, encompassing the Permian to Early Cretaceous strata, are affected by the normal faults caused by reactivation of the Variscan thrusts (see Section 5). The structure is complex and the Triassic rocks were deposited in several different basins, with different lithologies (Downing and Gray, 1986) and the hydraulic connection between these basins is unclear. Above the Gault Formation, the succession is relatively complete, and these younger formations are affected by Cenozoic folding (see Section 5). In this younger sedimentary cover sequence the Chalk Group is a principal aquifer and is extensively exploited. It is a major source of groundwater in the region. Groundwater in both the Chalk and Lower Greensand aquifers typically remains potable down to depths of the order of 300 to 400 m.

Regional groundwater flow in this relatively shallow, young cover sequence is predominantly down dip from the recharge areas over the high ground to the north of region, e.g. over the South and North Dorset Downs, Cranbourne Chase, Salisbury Plain and the Hampshire and South Downs, into the confined zones of the aquifers and towards the centre of the Cenozoic Hampshire Basin. The southern boundary to the region, the coastline of the English Channel, acts as a constant head boundary. This regional picture of groundwater flow is disrupted by the effects of faulting and folding on sub-regional to local-scale hydrogeology along the steep east–west-trending structures on the south limb of the Hampshire Basin Syncline.

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

- a groundwater system in the cover sequence of Palaeogene to younger Cretaceous sediments (down to the base of the Gault Formation) that crop out within the region and receive direct groundwater recharge
- a groundwater system in the cover sequence of older Cretaceous and Jurassic sediments from the Lower Greensand Group to the Lias Group that crop out within the region and receive direct groundwater recharge
- a groundwater system consisting of older sediments and low permeability basement rocks of Triassic and older age that are found at or below the depth range of interest and do not receive direct groundwater recharge

Rocks from the two highest groundwater systems are found extensively in the depth range of interest across the region. There are a number of potential pathways for groundwater movement between the groundwater systems, principally associated with regional-scale structures and with anthropogenic features (e.g. boreholes). These potential pathways for groundwater movement between units and groundwater systems are discussed after a description of each of the three groundwater systems.

6.3.1 Hydrogeology of the Palaeogene to younger Cretaceous (Gault Formation) groundwater system

6.3.1.1 PALAEOGENE ROCKS

The Palaeogene deposits of the region are of predominantly unconsolidated sands and clays (see Section 2) that are preserved as a relatively thick sequence in the central and southern part of the region. The deposits are only in the depth range of interest in a small area of the region (northern half of the Isle of Wight and adjacent parts of mainland Hampshire), the majority of the deposits being above the depth range of interest. However, they act to confine the underlying Chalk Group aquifer towards the centre of the Hampshire Basin, and sandier intervals in the Palaeogene rocks are locally developed for groundwater resources, typically to depths of a few tens of metres. There is no systematic information on the hydrogeology of the Palaeogene deposits in the active zone of groundwater exploitation and no information about these units in the depth range of interest in the reviewed literature.

Within the Solent Group, small supplies have been obtained from the Hamstead Member of the Bouldnor Formation, Bembridge Limestone Formation and Headon Hill Formation (Jones et al., 2000; Hopson and Farrant, 2015). In the Barton Group, the Barton Clay Formation is a relatively low permeability unit overlain and underlain by more permeable formations, with a spring line developed at the junction of the overlying sands and the Barton Clay Formation. Although the Chama Sand Formation and arenaceous horizons in the Barton Clay Formation have yielded small groundwater supplies, the Becton Sand Formation forms the more reliable aquifer, due to being relatively clay free (Jones et al., 2000). The Boscombe Sand Formation has springs issuing from it, but is rarely used for water supply (Jones et al., 2000). It forms a multilayered aquifer with the underlying Branksome Sand Formation (Bristow et al., 1991). A spring line occurs at its base in the Ringwood district (Barton et al., 2003). At Fawley (Figure 3), a 180 m deep borehole commencing in Barton Group had fresh groundwater; Edwards and Freshney (1987) reports that total hardness is generally <200 mg/l (as $CaCO_3$).

The upper part of the London Clay Formation can form local aquifers, particularly the uppermost Whitecliff Sand Member (although drilling into this aquifer in the Fawley area did not prove as productive as expected) (Jones et al., 2000). Water quality is variable, sometimes high in iron and brackish in the coastal belt (e.g. southern part of Hayling Island). The Reading Formation is generally sandier in the northern part of the Hampshire Basin (Jones et al., 2000). Where sandy it can be in hydraulic continuity with the underlying Chalk Group (e.g. around Southampton, IGS and SWA, 1979), with upward leakage into the basal sands (Jones et al., 2000). In the western, southern and eastern parts of the basin, the formation is predominantly composed of clay and unproductive for water supply. The water chemistry of the Reading Formation is generally similar to that of the underlying Chalk Group.

6.3.1.2 CHALK GROUP

The Chalk Group is a principal aquifer and the most important aquifer across the region, typically being exploited to a depth of about 100 m below the water level. It consists of two subgroups, the upper White Chalk Subgroup that comprises soft white chalk with discrete marl seams, nodular chalk units, sponge-rich and flint seams, underlain by the Grey Chalk Subgroup, comprising an upper unit of pale grey to off-white blocky chalk with a lower part of rhythmic alternations of marls and marly chalk with firm white chalk. The lower part of the Grey Chalk Subgroup is absent in the south of the region. The Chalk Group is overlain in the central and southern parts of the region by thick Palaeogene deposits that increasingly confine the group to the south and underlain by the Upper Greensand Formation with which it is generally in good hydraulic continuity.

Permeability of the Chalk Group is primarily a function of the density, connectivity and degree of secondary development of the pervasive fracture network and stratigraphical discontinuities and is best developed towards the surface of the Chalk Group. The fractures decline with depth due to increased overburden, changes in lithology and a general reduction in circulating groundwater (Hopson, 2008).

Allen et al. (1997) divides the Chalk Group at outcrop in the Hampshire region into four subregions: south Dorset and the Isle of Wight; Cranborne Chase; Salisbury Plain, and Hampshire. Based on a summary of pumping test data, it notes that the permeability of the Chalk Group in south Dorset and the Isle of Wight is about an order of magnitude lower that the other three areas. Note that the Hampshire region also includes the southern part of the Marlborough Downs and the south-west corner of the South Downs Chalk; these have been dealt with in the London and the Thames Valley and Wealden district region reports respectively.

Karst is present in the Chalk of the Hampshire region, but is heterogeneously developed. The area with the greatest density of karst solution features in the Chalk occurs in south Dorset (71–90/100 km^2), while Salisbury Plain has one of the lowest (<5/100 km^2) (Allen et al., 1997). The development of surface karst features is strongly associated with the edge of the overlying Palaeogene strata. Swallow holes and dolines are found in both recharge and discharge areas. There is enhanced development of dolines and other solution features on the northern flanks of the Portsdown Anticline between Soberton and Walderton (Jones et al., 2000). Solution features are related to the geomorphic setting and presence/absence of low permeability cover, but lithology, fracture style, geological structure, flint content, porosity, fissure permeability and anthropogenic activity are also factors. Stream sinks occur at the margin of the Palaeogene cover. Tracer tests around Horndean indicate rapid flow pathways to large springs at Bedhampton (Atkinson and Smith, 1974).

At outcrop, Chalk Group water is hard and of calcium-bicarbonate type. In the unconfined aquifer, chloride concentrations vary with distance from the coast. The oxidising conditions predominantly found in the unconfined Chalk Group aquifer give way rapidly to a reducing environment as the aquifer becomes confined beneath Palaeogene deposits. However, older, fresh groundwater can be found in the confined aquifer towards the centre of the Hampshire Basin. There are problems in assigning an age to this groundwater, but beneath Wareham the bulk of the Chalk Group water to a depth of 300 m has been ascribed a likely Holocene age (Edmunds et al., 2002). Water quality from a 369 m deep borehole at Otterbourne (Figure 3) that terminated in 14 m of Upper Greensand Formation had a TDS of 345 mg/l, and a total hardness of 244 mg/l (as $CaCO_3$) and Cl 28 mg/l (Burley et al., 1984). The Chalk Group below 140.7 m of overburden in the 403-m-deep borehole at Southampton Common (Figure 3) produced water with a TDS of 1310 mg/l, Na 351 mg/l and Cl 570 mg/l (Whitaker, 1910), and another 335-m-deep borehole at Southampton (Figure 3) reached Chalk Group at 189 m and produced slightly brackish water (Edwards and Freshney, 1987), with a chloride concentration of 700 mg/l.

6.3.1.3 UPPER GREENSAND FORMATION

The Upper Greensand Formation comprises of fine-grained, silty, glauconitic sand and sandstone. It is designated as a principal aquifer although within the region it is a much less important source than the overlying Chalk Group with which it can be in hydraulic connection. There is no systematic information on the hydrogeology of the Upper Greensand Formation in the zone of active groundwater exploitation and very limited information about it in the depth range of interest in the reviewed literature.

The Upper Greensand Formation receives some recharge from the Chalk Group with which it is in partial hydraulic continuity in the Salisbury district, Hampshire (Institute of Geological Sciences and Southern Water Authority, 1979), but may not be in hydraulic continuity further west (Institute of Geological Sciences and Wessex Water Authority, 1979); e.g. at Brixton Deverill [486300 138800] south of Warminster in Wiltshire, heads in the Upper Greensand Formation are slightly higher than in the Chalk Group due to the confining effects of the basal West Melbury Marly Chalk Formation (Bristow et al., 1999). In the south of the Isle of Wight, the Chalk Group is predominantly unsaturated with water draining down into the underlying Upper Greensand Formation with which it is in hydraulic continuity (Jones et al., 2000). In the Shaftesbury district, springs issue from many different levels within both the ‘malmstone’ (calcareous or cherty siltstone) and sands, as well as its junction with the Gault Formation (Osborne White, 1923). Hopson (2008) also notes that preferentially cemented fracture flow occurs in the Upper Greensand Formation.

The water in the Upper Greensand Formation aquifer is hard (Osborne White, 1923) and similar to that in the Chalk Group (Institute of Geological Sciences and Wessex Water Authority, 1979), but the degree of mineralisation is variable. Shallow groundwater can be saline in places, however, slightly brackish fresh water was found at 626 m in the Upper Greensand Formation at Marchwood 1 Borehole (Figure 3) with a total dissolved solids of 5350 mg/l.

6.3.1.4 GAULT FORMATION

The Gault Formation, a micaceous silty clay with a typically transitional junction with the Upper Greensand Formation above (see Section 4). It progressively oversteps older Cretaceous and Jurassic rocks to eventually rest on the Lias Group near Lyme Regis and Triassic rocks further west in Devon in the adjacent South-west England region (Melville and Freshney, 1982). There is no systematic information on the hydrogeology of the Gault Formation in the zone of active groundwater exploitation and no information in the depth range of interest in the reviewed literature.

In the Gault Formation, porosity is dominated by intergranular pores, but fracturing in the formation is common, and is likely to affect the bulk permeability of the Gault Formation (Forster et al., 1994). The near-surface hydrogeology is strongly controlled by the influence of weathering and stress release which is observed to a depth of at least 10 m, but is typically 3 m; the depth of chemical weathering varies but rarely extends to 10 m (Forster et al., 1994). Chinsman (1972) finds that permeability, and its variability, in the Gault Formation clay decreased with increasing overburden. This effect was irrespective of its state of weathering or disturbance and he attributed it to the closure and constriction of fissures (Forster et al., 1994).

6.3.2 Hydrogeology of the older Cretaceous (Lower Greensand Group) to Jurassic groundwater system

6.3.2.1 LOWER GREENSAND GROUP

The Lower Greensand Group comprises sands, ferruginous and glauconitic sands, sandstones, sandy clays and clays and ironstones (Melville and Freshney, 1982). It is designated as a principal aquifer, although within the region it is a much less important groundwater source than the Chalk Group aquifer. It is generally absent at outcrop in the west of the region where the Gault Formation oversteps the Lower Greensand Group onto Kimmeridge Clay Formation to Great Oolite Group strata. It is also absent at depth below the south-west part of the region, where the Gault Formation unconformably overlies the Great Oolite Group. Further east it is absent to the south of the Cranborne Fault. It is highly permeable (compared with the Gault Formation) but regionally very variable in thickness. Due to its restricted outcrop area this results in poor recharge potential, so that its deeper waters can be saline. It has been inferred from this that it is effectively confined by the overlying Gault Formation (Alexander, 1983; Forster et al., 1994). There is no systematic information on the hydrogeology of the Lower Greensand Group in the zone of active groundwater exploitation and no information in the depth range of interest in the reviewed literature.

Downing and Gray (1986) states the permeability values from core analysis of the sandstone penetrated in the Marchwood 1 borehole (Figure 3), ranged up to 9.9×10^{-13} m^2. A 457 m deep borehole at Sompting (in the adjacent Wealden district region) proved 49 m of Early Cretaceous sandstone below 404 m overburden thickness; 35 m of medium to coarse-grained, uncemented or poorly cemented sandstone underlain by 14 m of fine-grained, clayey, glauconitic sandstone. The sequence yielded water at 21°C, with average permeability estimated to be about 2×10^{-12} m^2 (Downing and Gray, 1986). Drilling fluid was lost in the Arreton 1 Borehole in the Lower Greensand Group indicating it was ‘fairly porous’.

Groundwater in the Lower Greensand Group is mainly of calcium-bicarbonate type (Shand et al., 2003), but softer than water from the Upper Greensand Formation (Osborne White, 1913). Deep boreholes on the outcrop of the Lower Greensand Group produce water with low mineralisation, and the water from more than 400 m depth in the Sompting Borehole was fresh with a total dissolved solids of 110 mg/l (Burley et al., 1984). However, quality deteriorates with increasing depths in Portsdown 2 and Marchwood 1 boreholes (Figure 3). Ages of 2000–4500 years have been obtained for three samples of water from the confined Lower Greensand Group on the Isle of Wight (Hopson and Farrant, 2015).

6.3.2.2 WEALDEN GROUP

The Wealden Group consists of interbedded thick sandstones, siltstones, mudstones, limestones and clay ironstones. It is absent in the west of the region (apart from south of the Needles Fault on the Isle of Purbeck and the Sandown Fault on the Isle of Wight). It is also absent to the north of the Mere Fault in the Vale of Wardour and further north, the Vale of Pewsey Fault. It is overstepped by Lower Greensand Group (west of around SU 38038 19000 and south of around SU 37196 28136). It is absent in the Southampton area, and hence not penetrated by the two deep boreholes there, where the Lower Greensand Group overlies Kimmeridge Clay Formation at Marchwood, and the Portland Group at Western Esplanade. There is no systematic information on the hydrogeology of Wealden Group in the zone of active groundwater exploitation and almost no information in the depth range of interest in the reviewed literature. Groundwater in the confined Wealden Group from samples from the Portsdown 2 borehole (Figure 3) has a total dissolved solids of 2314 and 6965 mg/l from sample depths of 665 and 759 m respectively (Burley et al., 1984).

6.3.2.3 PORTLAND STONE FORMATION

The Portland Stone Formation of the Portland Group is a principal aquifer. It comprises thick-bedded, ooidal, shelly and bioturbated limestones with nodular cherts and locally sandy, lime mud-rich limestone. There is no systematic information on the hydrogeology of Portland Stone Formation in the zone of active groundwater exploitation and almost no information in the depth range of interest in the reviewed literature.

The Portland Group limestones tend to be cemented, resulting in relatively low intergranular permeability. Water movement is through fractures that have been enlarged by solution with high yields obtained where openings are closely interconnected. At and near outcrop the limestones may have high transmissivity due to their fissure flow characteristics (Hopson, 2008). Water quality is hard to very hard, with high calcium bicarbonate (Hopson, 2008). The water from the Portland Group at Friar Waddon (Figure 3), below 62 m of overlying Purbeck Group had a total dissolved solids of 304–321 mg/l, however, deeper water from 865 m in Portsdown 2 Borehole (Figure 3) was highly mineralised with a total dissolved solids of 14 920 mg/l.

6.3.2.4 KIMMERIDGE CLAY FORMATION AND AMPTHILL CLAY FORMATION

The Kimmeridge Clay Formation comprises alternating beds of dark grey mudstone, highly calcareous mudstone, siltstone, silty mudstone, bituminous mudstone (oil shale) and limestone (and no information in the depth range of interest in the reviewed literature. Kimmeridge Clay Formation waters contain iron and often have a high total dissolved solids content (Jones et al., 2000). A 26 m deep source at Manston (Figure 3) had a total dissolved solids of 3465 mg/l (Bristow et al., 1995).

6.3.2.5 CORALLIAN GROUP

The Corallian Group is a complex succession of interdigitating limestones, marls, sandstones, sands, siltstones, silts, spiculites and mudstones (Wright and Cox, 2001). Mudstones are typically a minor component of the group (see Section 3). The lower boundary is of a transitional nature with the Oxford Clay Formation. The Corallian Group is present over most of the region, but is cut out locally by the Cranborne Fault. There is no systematic information on the hydrogeology of the group and almost no information in the depth range of interest in the reviewed literature. At outcrop water quality is good, but it becomes more mineralised at depth downdip with highly mineralised water found in Fordingbridge 1 (total dissolved solids of 19 993 mg/l) and Encombe 1 (total dissolved solids of 93 725 mg/l) boreholes (Figure 3) at 772 and 580 m respectively (Burley et al., 1984; see Table 4).

Table 4 Water quality from confined Corallian Group (Burley et al., 1984).

Location	**Type of sample**	**Sample depth (m)**	**Temp (°C)**	**pH**	**Na mg/l**	**K mg/l**	**Ca mg/l**	**Mg mg/l**	**HCO_3 mg/l**	**SO_4 mg/l**	**Cl mg/l**	**TDS mg/l**
Fordingbridge 1	DST	772		7.7	7295	11	341	141	179	17	12 100	19 993
Encombe 1	DST	580	29	7.5	33 007	179	1400	1464	230	52	57 510	93 725

DST=drill stem test; NGR = national grid reference.

6.3.2.6 KELLAWAYS FORMATION AND OXFORD CLAY FORMATION

The Oxford Clay Formation is a succession of silicate mudstone with sporadic beds of argillaceous limestone nodules (see Section 3). It is underlain by the Kellaways Formation comprising of sandy limestone (Kellaways Sand Member) over clays with nodules and silty layers (Kellaways Clay Member) (Melville and Freshney, 1982). The Kellaways Sand Member forms a local aquifer in the Cotswolds, but there is no systematic information on the hydrogeology of either the Kellaways or Oxford Clay formations and almost no information in the depth range of interest in the reviewed literature. The weathered clays of the Oxford Clay and Kellaways formations provide ferruginous and often poor-quality groundwater and are typically highly mineralised (total dissolved solids in the range 30 346–47 625 mg/l) at depths between 545 and 833 m (Burley et al.,1984).

Table 5 Water quality from confined Kellaways Formation (Burley et al., 1984).

Location	**Type of sample**	**Sample depth (m)**	**Temp. (°C)**	**pH**	**Na mg/l**	**K mg/l**	**Ca mg/l**	**Mg mg/l**	**HCO_3 mg/l**	**SO_4 mg/l**	**Cl mg/l**	**TDS mg/l**
Encombe 1	DST	833		8.0	11441	61	272	129	468	463	17750	30346
Kimmeridge 2	DST	545	28	7.4	14533	114	770	294	237	518	24140	40485

DST=drill stem test, NGR = national grid reference

Great Oolite Group

The Great Oolite Group within the region consists of a number of interbedded limestones and mudstones (see Section 4). The main mudstone intervals are the Frome Clay Formation and the Fuller’s Earth Formation, which are best developed in the thicker Great Oolite Group successions of south Dorset (Rhys et al., 1982). Toward the north of the Hampshire region (approaching the Cotswold–Weald shelf (Figure 11) the Great Oolite Group thins and mudstones are progressively replaced by thicker amalgamated predominantly ooidal limestones (Cox and Sumbler, 2002), these are considered a principal aquifer. This limestone-dominated succession continues downdip into the deeply confined basin and forms the Great Oolite Group succession across the whole of the eastern part. Across the region, there is almost no information in the depth range of interest in the reviewed literature.

The Great Oolite Group is a fissured limestone with an abundance of springs at outcrop and is a significant aquifer for water supply. Where it lies under the Oxford Clay Formation, its waters are non-potable (Alexander, 1983; Forster et al., 1994). Small supplies of groundwater have been obtained from the Fuller’s Earth Rock Member, and the Forest Marble Formation limestones in conjunction with the overlying Cornbrash Formation. In the Wytch Farm oilfield (Figure 3) the presence of oil in the Cornbrash Formation and Forest Marble Formation (Bristow et al., 1991), indicate they have some permeability at depths of around 800 m. Burley et al. (1984) reports total dissolved solids of 67 034 mg/l from 1347 m from the Winchester 1 Borehole (Figure 3) and 21 058 mg/l from 576 m from the Kimmeridge 3 Borehole (Figure 3) for the Great Oolite Group (see Table 6).

Table 6 Water quality from confined Great Oolite Group (from Burley et al., 1984).

Location	NGR	Type of sample	Sample depth (m)	Temp. (°C)	pH	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	HCO_3 mg/l	SO_4 mg/l	Cl mg/l	TDS mg/l
Winchester 1	450340 128490	DST	1246	48	6.5	21470	161	3408	681	154	239	41000	67034
Kimmeridge 3	389780 078950	DST from FM sst	576	34		7704	10	296	122	271	1078	11715	21058

DST=drill stem test; NGR = national grid reference; FM sst = Forest Marble Formation sandstone.

6.3.2.7 INFERIOR OOLITE GROUP

The Inferior Oolite Group, a principal aquifer, is present throughout the area, apart from an area centred on the part of the Solent on the north-west side of the Isle of Wight. It comprises oolitic (often ferruginous) limestone, shell-fragmental oolitic limestone or sandy limestone. Across the region, there is almost no information in the depth range of interest in the reviewed literature for this unit. Water samples from three boreholes within the Inferior Oolite Group in the depth interval 881 to 1369 m are highly mineralised with total dissolved solids in the range 16 116 to 131 736 mg/l (Burley et al., 1984).

6.3.2.8 LIAS GROUP

The Lias Group is a lithologically varied unit comprised of friable sands with hard calcareous cemented sandstone beds, ferruginous limestone, silty and sandy mudstone, and laminated shales. The uppermost Bridport Sand Formation, a principal aquifer, is relatively permeable and is often in hydraulic continuity with the overlying Inferior Oolite Group, providing intergranular storage at the base of the fractured limestone aquifer. The lower permeability part of the sequence consists of the Dyrham to Blue Lias formations. Across the region, there is limited information in the depth range of interest in the reviewed literature for this unit. There are many springs that issue from the Dyrham Formation, with several previously being used for public supplies in the Symondsbury, Morecombelake and Chideock area and some forming rivers. The formation is tapped by many shallow wells in this area, where it is sandy and also in hydraulic continuity with the overlying Beacon Limestone Formation (Jones et al., 2000).

Shand et al. (2004) describes the baseline water quality of the Bridport Sand Formation. Generally, the shallow water quality is of calcium-bicarbonate type. Groundwater quality from shallow sources into the

Lower Lias is generally hard and often poor with hydrogen sulphide from decomposing pyrite in the shales. Salinity in the Jurassic of the Hampshire Basin generally increases with depth both stratigraphically and relative to sea level, with maximum salinities of 96 000 mg/l chloride found in the Lower Lias (Downing and Gray, 1986). For the confined Bridport Sand Formation, Burley et al. (1984) reports relatively high values for total dissolved solids in the range 66 483 to 143 470 mg/l in the depth interval 263 to 1180 m.

6.3.3 Hydrogeology of the Triassic to Devonian sedimentary and basement rocks

6.3.3.1 MERCIA MUDSTONE GROUP

The Mercia Mudstone Group comprises mudstone with minor sandstone and intervals of evaporite (see Section 4). Dolomitic conglomerate-type marginal facies deposits (limestone, siltstone, sandstone, breccia) (Hopson, 1999; Farrant et al., 2011) comprise a principal aquifer at, and near, outcrop where they are well-fractured and in hydraulic continuity with the underlying karstic Carboniferous Limestone Supergroup in the adjacent Bristol and Gloucester region. However, across the Hampshire region, there is no information on these deposits in the depth range of interest in the reviewed literature for this unit.

Locally the ability of the Mercia Mudstone Group to yield water is influenced by the proximity of sandy layers within it. Permeability through discontinuities may be influenced by the depth of weathering (it can exceed 30 m, but is generally 10 to 15 m, and the presence of infilling material such as halite or gypsum or by cavities left by solution (Hobbs et al., 2002).

6.3.3.2 SHERWOOD SANDSTONE GROUP

The Sherwood Sandstone Group, a principal aquifer, consists of a series of breccias, conglomerates and sandstones. The deposition and facies are controlled by differential subsidence related to movement on the major growth faults (Downing and Gray, 1986). The dominant control on hydrogeology is the degree of cementation that affects permeability. Most of the available hydrogeological information for the sandstones comes from the Southampton and Marchwood 1 geothermal energy boreholes (Figure 3) that lie east of the Hampshire–Dieppe high with permeabilities reported up to $4.9\text{x}10^{-12}$ m^2 (Downing and Gray, 1986). There was no evidence of fracture flow in the sandstone at depth, but there is leakage from the low permeability to the high permeability sandstone layers. These thin water-bearing layers may not persist for great distances, due to lateral sedimentological or diagenetic changes or faulting. Analysis of downhole pressure data on the Southampton and Marchwood 1 boreholes, concluded that they are either in a closed block of some 200 km^2 or in a narrow wedge (Downing and Gray, 1986). In the deepest part of the basin, the Winterborne Kingston Borehole (Figure 3) proved the top of the Sherwood Sandstone Group at 2232 m and had permeabilities similar to those at Southampton (Downing and Gray, 1986). Permeability values decrease drastically due to cementation near the Purbeck–Wight disturbance and the Cranborne Fault and these structures are considered to act as hydraulic barriers to the Dorset basin (Downing and Gray, 1986). The residence time for fluids in the Sherwood Sandstone Group from the Marchwood 1 Borehole have a median age of about 15 Ma (Miocene) (with a range of 1.25–85 Ma) (Downing and Gray, 1986; Darling et al.,1997). Downing and Gray (1986) conceptualises flow at intervals during the Alpine inversion period with little subsequent movement except for further exchange by diffusion between adjacent formations allowing salinities to increase.

6.3.3.3 AYLESBEARE MUDSTONE GROUP

In south Dorset, the Permian Aylesbeare Mudstone Group typically comprises mudstones interbedded with sandstone and siltstone, and fining-up conglomerates interbedded with sandstones that may overlie a basal breccia developed on the Variscan unconformity (see Section 4). Across the region, there is no information on the hydrogeology of this unit in the depth range of interest in the reviewed literature for this group.

6.3.3.4 CARBONIFEROUS LIMESTONE SUPERGROUP

The Carboniferous Limestone Supergroup, a principal aquifer where it is at outcrop in other regions, is only present at depth in the Hampshire region. The reviewed literature contains no information on the physical or chemical properties of the Carboniferous Limestone Supergroup aquifer in the region, including no groundwater chemistry from the deep aquifer in the Hampshire region being quoted in Burley et al. (1984). Data from other regions indicate that the limestones are generally well cemented, with low intergranular (matrix) porosity and permeability (Allen et al., 1997). Where present at outcrop in other regions, the Carboniferous Limestone Supergroup limestones can develop a network of solution-enlarged fractures or conduits through which groundwater flow occurs (Allen et al., 1997), however, there is no evidence from the reviewed literature for karstic features within the unit in region.

6.3.3.5 OLDER CARBONIFEROUS SEDIMENTS AND DEVONIAN AND OLDER BASEMENT ROCKS

These include the older Carboniferous Teign Valley and Tintagel groups and the Mid and Late Devonian slates, mudstones, siltstones, sandstones with limestone, and tuffs and basalts of the basement rocks of the region. There is no hydrogeological information on these units within the Hampshire Basin. However, there is some information on the shallow hydrogeology of these rocks available for the South-west England region where they are present at outcrop.

6.4 EVIDENCE FOR CONNECTION BETWEEN GROUNDWATER SYSTEMS

6.4.1 Separation of aquifers

In the uppermost groundwater system in the region, the Gault Formation is hydrogeologically important in separating groundwaters in the overlying Chalk Group and/or Upper Greensand Formation from that in the Lower Greensand Group (IGS and SWA, 1979) (as well as other permeable formations (e.g. the Great and Inferior Oolite groups) in the groundwater system immediately below it. Jones et al. (2000) states that some downward vertical groundwater flow occurs through the Gault and Kimmeridge formations 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. The Gault Formation is thus an important modifier of the regional hydrogeological regime. It restricts groundwater fluxes through it and therefore helps to control the recharge and discharge of adjacent aquifers (Forster et al., 1994), acting as an imperfect confining or leaky layer above the different aquifers on which it rests (Forster et al., 1994). The Great Oolite Group underlies the Gault and Upper Greensand formations to the north and east of Bridport in south-west England (Forster et al., 1994). The Great Oolite Group has a higher head than the Corallian strata at Harwell (London and the Thames Valley region, where it contains more limestone), implying upward flow through the Oxford Clay Formation (Alexander, 1983). If there is a similar upward head gradient where it lies directly below the Gault and Upper Greensand formations in the Hampshire region, a similar situation could occur (Forster et al., 1994). However, in the west of England the Gault Formation becomes progressively siltier and passes laterally and vertically into the Upper Greensand Formation. Thus the overlying Gault and Upper Greensand formations in the south-west may be significantly permeable, and with a downward head gradient it could leak recharge to the Great Oolite Group and dampen groundwater level fluctuations within it. Some outliers of Chalk Group lie on top of the Upper Greensand in this area and may contribute water to it in turn. Where the Gault and Upper Greensand formations are of very low permeability, this will highlight the low storage potential of the limestone and will amplify groundwater level variations, which can result seasonally in artesian conditions (Alexander, 1983; Forster et al, 1994).

The presence of oil in five separate reservoirs below Wytch Farm (Sherwood Sandstone Group, Bridport Sand Formation, Frome Limestone Member (of Frome Clay Formation), Forest Marble Formation and the Cornbrash Formation), indicates their isolation from each other by fault offset and the capping effect of the overlying beds. The Sherwood Sandstone Group is isolated by the Mercia Mudstone Group and the Jurassic reservoirs are all overlain by the Oxford Clay Formation and Gault Formation.

6.4.2 Geological pathways

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

There are no documented thermal springs (>15°C) in the area. There is a note of a temperature of 17.5°C being recorded on 12 September 1872 for a spring from the Upper Greensand Formation near Ventnor used for public supply (Whitaker, 1910). This may be issuing from the Wroxall–Ventnor railway tunnel and be derived from the Upper Greensand Formation below the Chalk Group under Wroxall Down. However, the same reference source records a temperature of only 10.4°C for a spring in this tunnel only two months later, on 16 November 1872.

6.4.3 Anthropogenic pathways

There are a large number of water supply wells and boreholes in the region, mainly into the Chalk Group; between the mid19th to early 20th centuries extensive adit systems were constructed from some of these sources. As well as the two deep geothermal energy boreholes around Southampton, the Hampshire region includes a large number of deep (1 to 2 km) boreholes, drilled for hydrocarbon exploration, to the Sherwood Sandstone Group, associated with the Wytch Farm oilfield in south Dorset (see Section 4), (as well as other less prolific oilfields described in Section 8) and others reaching Palaeozoic rocks. However, there is no information in the reviewed literature that suggests that any of these structures acts to hydraulically connect any of the groundwater systems.

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

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

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

7.2 GLACIATION

7.2.1 A UK-scale context

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

It is clear from the recent geological record that glaciers have been repeatedly active within the UK landscape over the past two and half million years (Clark et al., 2004; Lee et al., 2011). Numerous periods of glaciation have been recognised, although the scale and extent of glaciers have varied considerably. Most glaciations have been comparatively small (i.e. highland glaciations), although some have been more extensive with glaciers expanding into lowland parts of the UK, i.e. lowland glaciations (Clark et al., 2004; Lee et al., 2011). Over the past half a million years, at least two continental-scale glaciations have affected the UK with ice sheets covering parts of lowland UK, on one occasion as far south as the London area (Figure 17; 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 Hampshire region is situated beyond the limits of continental and lowland scale glaciation (Figure 17) during the last two and half million years (Quaternary Period: RWM 2016b; Lee et al., 2015). 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 and / or a glacier forebulge relating to the glaciation of an adjacent onshore area (e.g. the Central England region). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (RWM 2016b). The extensive coastline of the Hampshire 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. Saline groundwater incursion may alter the temporal and spatial patterns of groundwater behaviour (RWM 2016b).

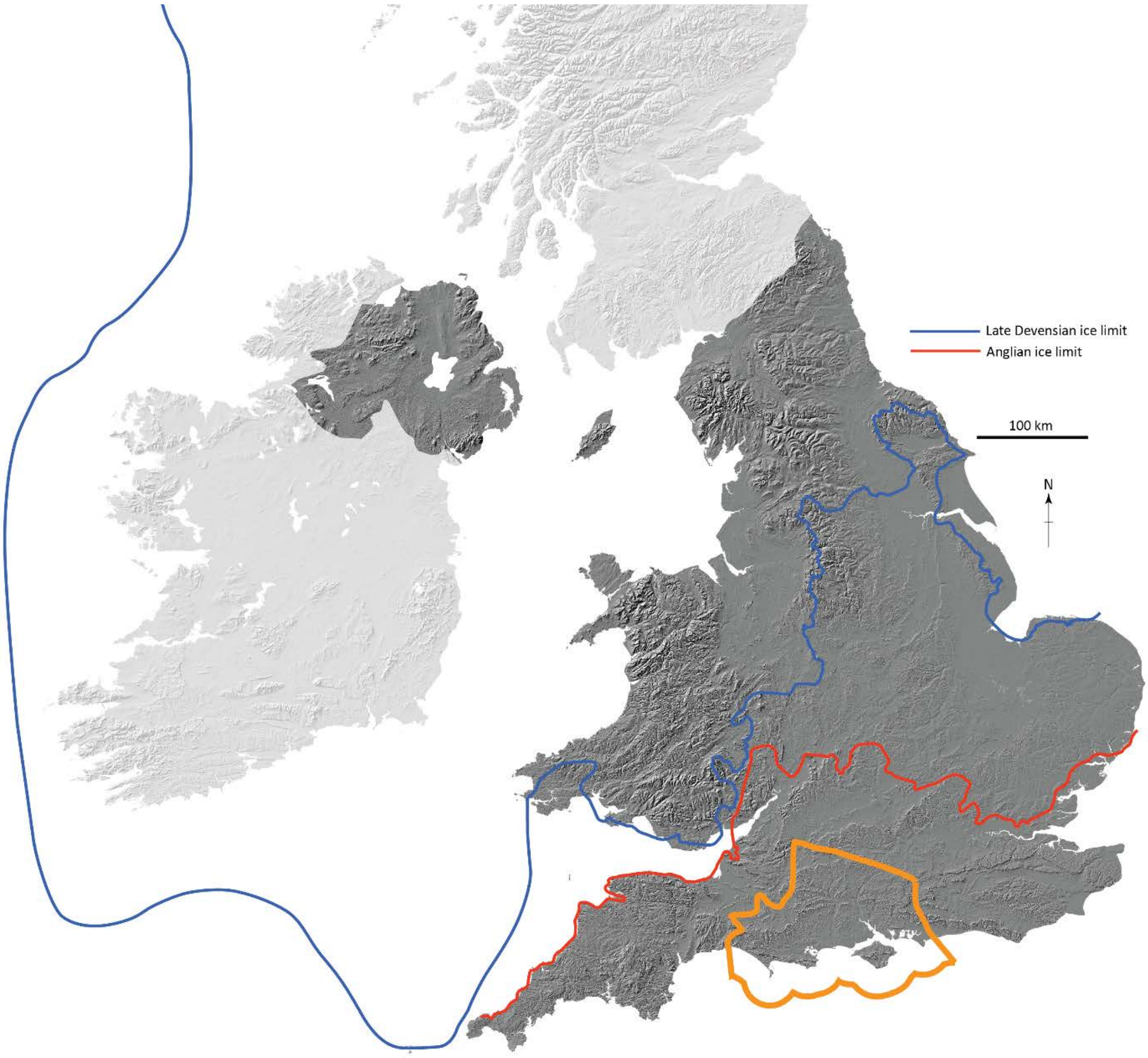


Figure 17 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and late Devensian (around 30 to 16 ka). The location of the Hampshire region is delineated by the orange line. Produced using Copernicus data and information funded by the European Union — EU-DEM layers © EEA.

7.3 PERMAFROST

7.3.1 A UK-scale context

Permafrost (frozen ground) occurs when the temperature of the ground remains below 0°C for at least two consecutive years (French, 2007). Permafrost, therefore, develops where average air temperatures are much colder than the present day and consequently there is potential for significant thicknesses of permafrost to develop over decadal to centennial timescales (Busby et al., 2014). It is also important to note that permafrost and glaciation are not synonymous. Whilst many glaciated areas are subjected to periglacial processes, not all areas affected by permafrost will become glaciated. For example, areas situated to the south of the major limits of glaciation in the UK (Figure 17) 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 Hampshire region will be subjected to the development of permafrost to a depth of a few hundred metres (Shaw et al., 2012; Busby et al., 2014). The development of permafrost can affect groundwater chemistry and behaviour (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 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 18). 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 18). 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).

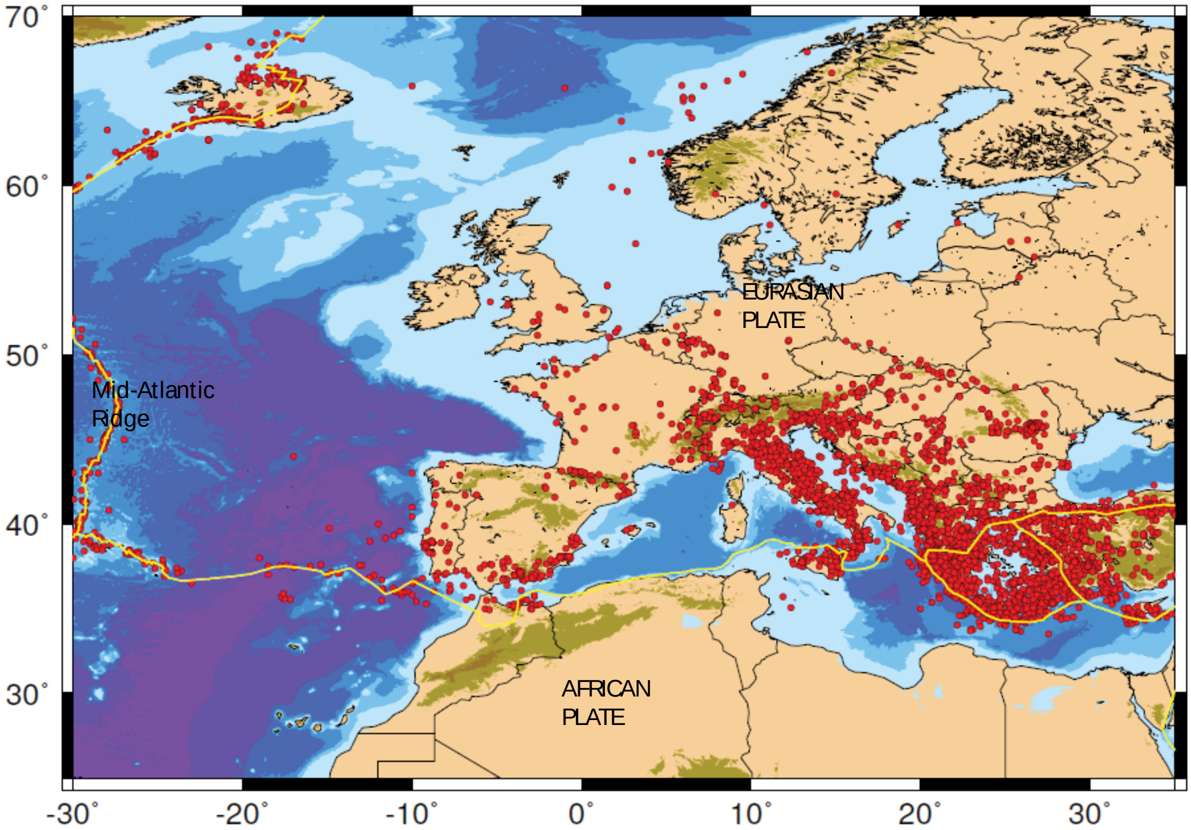


Figure 18 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

7.4.2 Seismicity catalogue

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

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

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

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

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

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

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

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

A requirement for any statistical analysis of seismicity is that one needs to know the extent to which the record of main shocks in an earthquake catalogue is complete. For example, some historic earthquakes that happened may not be present in the catalogue because no record of them survives to the present day. Normally, completeness improves with time (better nearer the present day) and also with magnitude (better for larger earthquakes). Thus one can describe a series of time intervals within which it is considered that the catalogue definitely contains all earthquakes above a certain magnitude threshold. This threshold value can be defined as the lowest magnitude at which 100 per cent of the earthquakes in a space-time volume are detected (Rydelek and Sacks, 1989). Therefore it is usually low for recent seismicity and gets progressively higher back in time. For this study we use the completeness estimates for the UK catalogue determined by Musson and Sargeant (2007), which are shown in Table 7. 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.

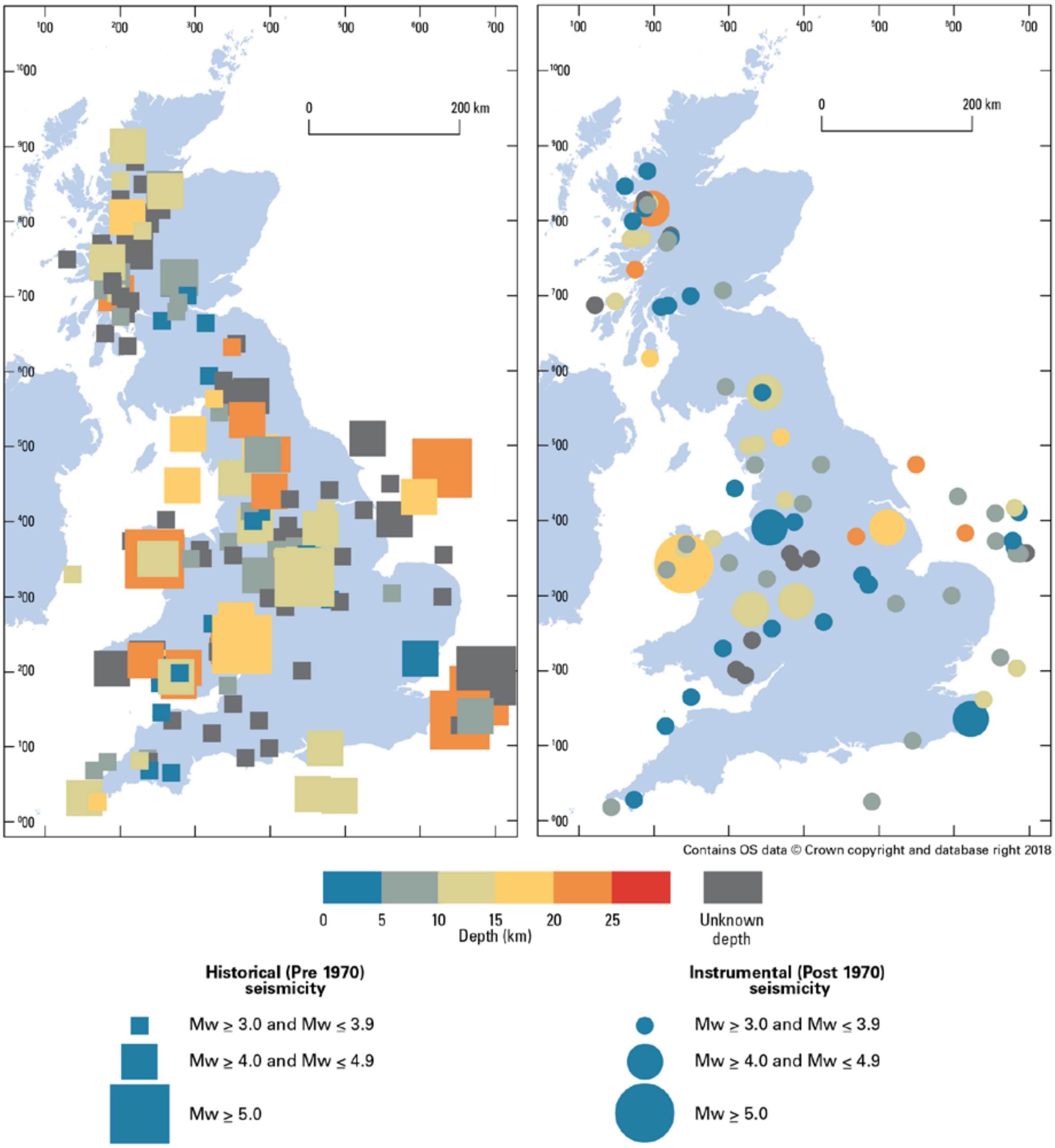
Table 7 Completeness values for the BGS seismicity catalogue (after Musson and Sargeant, 2007).

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 19 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 19), 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 series 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).



Contains OS data © Crown copyright and database right 2018

Figure 19 Distribution of the mains shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

7.4.3 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 20 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.

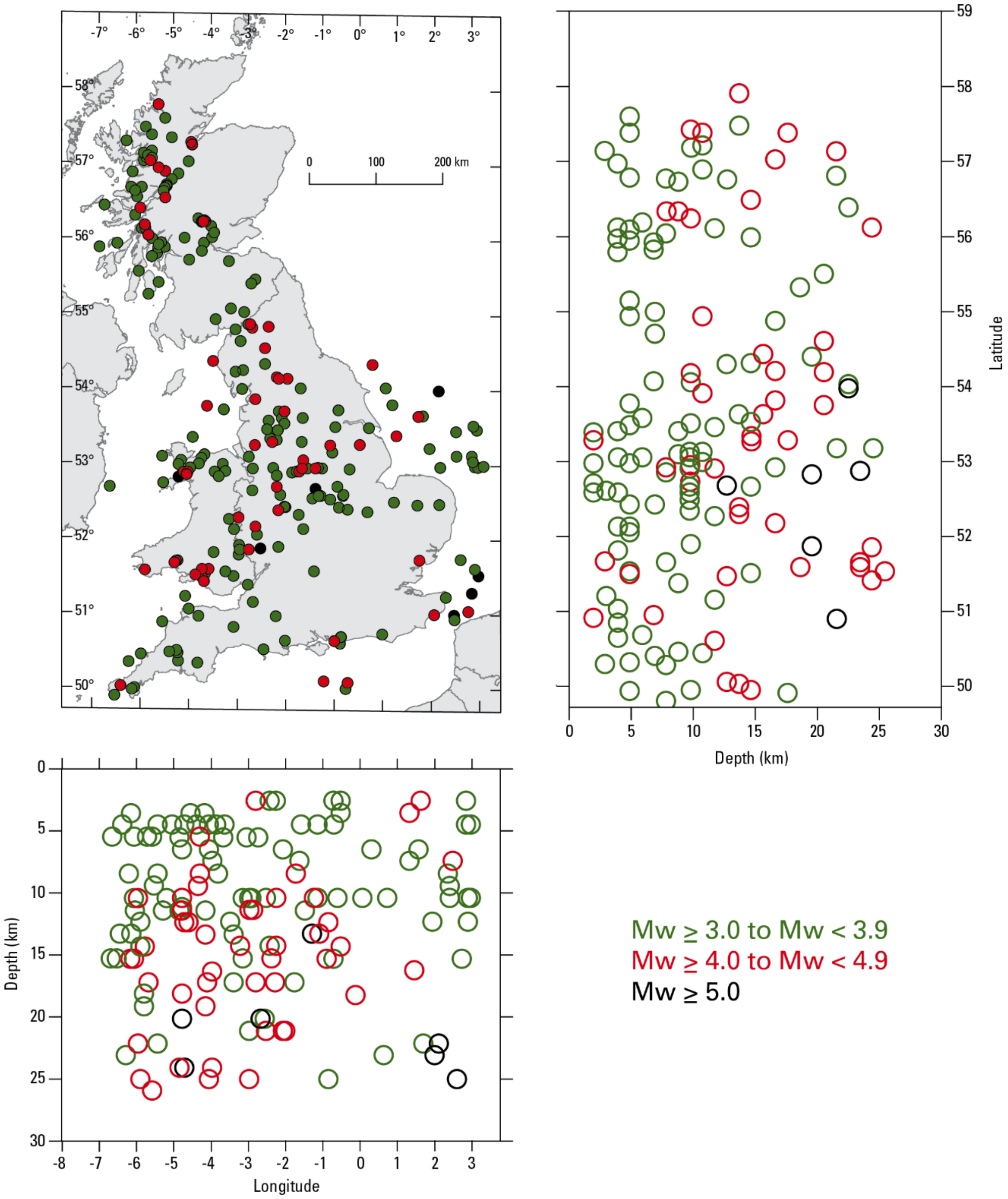


Figure 20 Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

7.4.4 Maximum magnitude

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

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

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

7.4.5 Earthquake activity rates

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

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

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

7.4.6 Impact of future glaciation

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

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

7.4.7 Conclusions

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

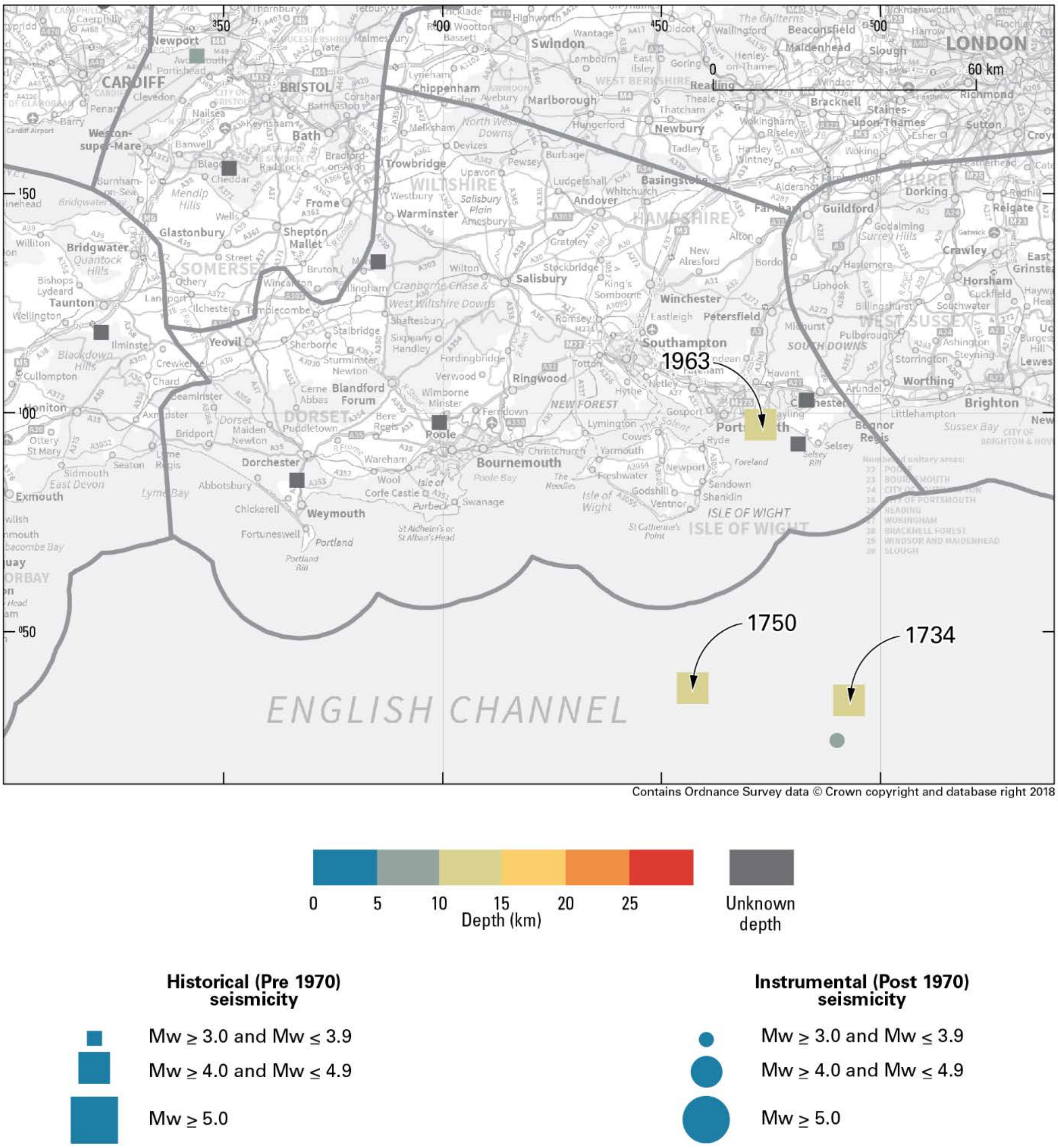
There are two crucial limitations in studies of British seismicity:

- The duration of the earthquake catalogue (approximately 700 years) is very short compared to the recurrence interval of large earthquakes in intraplate areas (thousands of years) and geological processes (millions of years). As a result, our understanding of earthquakes and earthquake generating processes is incomplete.
- The lack of surface ruptures does not allow us to associate seismic activity that has occurred with specific tectonic structures.

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

7.4.8 A regional perspective

Earthquake activity in the Hampshire region is lower than in many other parts of Britain (Figure 21). There is only one record of an earthquake with a magnitude of 4.0 Mw or greater: the magnitude 4.4 Mw Chichester earthquake of 1963 (Neilson et al., 1984). The epicentre was between Portsmouth and Chichester and it was felt across Sussex and Hampshire. Earthquakes with magnitudes of 4.2 and 4 Mw occurred in the English Channel in 1734 and 1750, respectively. The 1734 earthquake was felt on both sides of the English Channel.



Contains Ordnance Survey data © Crown copyright and database right 2018

Figure 21 Historical and instrumentally recorded earthquakes in the Hampshire region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

This section explains what is known of mineral resources in the Hampshire 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 that 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 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

Figure 22 shows the distribution of mineral resources in the region. Deep mineral extraction in the region is exclusively for hydrocarbons; The Wessex Basin is the UK’s most productive conventional onshore oil and gas area. A large part of the region has deep mudstones that might be prospective for shale gas and oil. Parts of the region have been investigated for geothermal energy potential and there is a geothermal power scheme operating in Southampton.

8.3 COAL AND RELATED COMMODITIES

There are no known coal deposits in the region.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

There is no exploitation of evaporite deposits in the region, however, bedded salt deposits of Triassic age occur in the region (see Section 4 for discussion on these). Salt deposits are present in the Dorset Halite Member of the Triassic Mercia Mudstone Group, which is concealed beneath Jurassic and younger rocks, and is known only from boreholes. Salt underlies at least 1200 km^2 of the south-west of this region from between Bridport to Poole. The Dorset Halite Member has never been exploited and it is highly unlikely to be utilised for salt production, because of its location and depth. However, thick, relatively pure, halite units could be considered for storage cavity purposes where depths are appropriate.

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. In the western extremity of the region, extending from Bath into the north-west corner of the region around Corsham, Jurassic limestone has been worked underground for building stone. All these workings are relatively shallow.

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 oilfields in the region, including the largest onshore oilfield in the UK at Wytch Farm. These are near Alton, Andover, Winchester, Horndean, Wareham (Wytch Farm), Kimmeridge and Moreton.

The Kimmeridge oilfield, discovered in 1959, was the first commercial discovery in the Wessex Basin. The discovery borehole for the Wareham oilfield was drilled in 1964, although production testing did not commence until 1970, with shut-in occurring in 1979 to conserve energy in updip accumulations. Production finally commenced in 1991. Wytch Farm was discovered in 1973 and has proved to be the most important find. Initially it was believed to be a modest discovery (30 million barrels). However, subsequent drilling proved deeper target horizons in the Sherwood Sandstone Group (Triassic) and it is now both the largest onshore oilfield in Europe and in the top ten of British fields, including those in the North Sea. The oilfield extends offshore far to the east of the discovery borehole.

In Hampshire, oil is being extracted from Humbly Grove, Stockbridge (incorporating Folly Farm and Goodworth and Horndean) (Figure 22). It is thought that following the initial success and discoveries made in this area in the 1980s further oil and gas discoveries will only be small in nature and likely to be satellite structures to the main fields.

A large area in the south-west of the region contains mudstones or shales that have been identified as having potential for shale oil and/or gas prospectivity. The area of the Wealden district region prospective for shale oil extends into the eastern part of the region between Farnham and Petersfield.

8.8 GAS STORAGE

The Hampshire region offer potential for underground gas storage, both in bedded salt deposits and porous rock (initially using depleted hydrocarbon fields). An underground gas storage facility is operational at the depleted Humbly Grove oilfield, south-east of Basingstoke. Planning permission was gained in 2003 for about 283 million cubic metres (mcm) (10 billion cubic feet (Bcf)) gas storage facility, which commenced storage operations on November 4th 2005. The storage horizon is the Great Oolite Group (Mid Jurassic) at around 982 m below OD (between around 910 and 950 m below NGS datum).

An underground gas storage facility was planned on the Isle of Portland, having gained planning consent in 2008. It was to use solution-mined caverns in the Dorset Halite Member, which varies in depth across the region from around 300–400 m, down to depths of 2.4 km in the south and extends offshore into the English

Channel area. It now seems likely that the underground gas storage facility will not proceed, in part because of the difficult technical aspects of the project and their effect on development costs. The halite beds extend offshore into the 20 km zone under consideration, but are likely to be deeper than 1000 m below NGS datum over much of the area. They are poorly known and thinner toward their limits.

In common with the adjacent Wealden district region, there is the potential to utilise depleted oil and gas fields for underground gas storage, although no proposals have been put forward to date.

8.9 GEOTHERMAL ENERGY

Hampshire is underlain by the thick sedimentary succession of the Wessex Basin, including the Sherwood Sandstone Group brine aquifer. Regional mapping of the Wessex Basin has inferred that in the deeper buried areas of the basin the Sherwood Sandstone Group could reach up to 3000 m depth, and potentially exceed 100°C at its base.

The region was evaluated by the Department of Energy for its geothermal energy potential in the 1980s, testing the Sherwood Sandstone Group. In 1986 two boreholes were drilled at Marchwood and Southampton (Figure 3) where geothermal gradients of 37°C per kilometre were confirmed, with a bottom hole temperature in Southampton of 74°C. The Southampton borehole was developed by Southampton City Council after the Department of Energy deemed the project uneconomic. The geothermal power scheme currently provides heating to the Southampton District Energy Scheme in the city centre.

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 23). These are related to the assessment and exploitation of oil. At Wytch Farm, the largest onshore oilfield in the UK, there are many multiple boreholes that are up to 9 km long but only to 2 km deep, drilled to exploit satellite reservoirs from central sites in an environmentally sensitive area. The region contains some of the most intensively drilled areas in the UK with up to 96 deep boreholes per square kilometre in some areas. The oilfields in the Hampshire region also contain numerous deep wells related to the active hydrocarbon production sites. There is a cluster of deep boreholes around Southampton city centre, some of which relate to the geothermal energy scheme there.

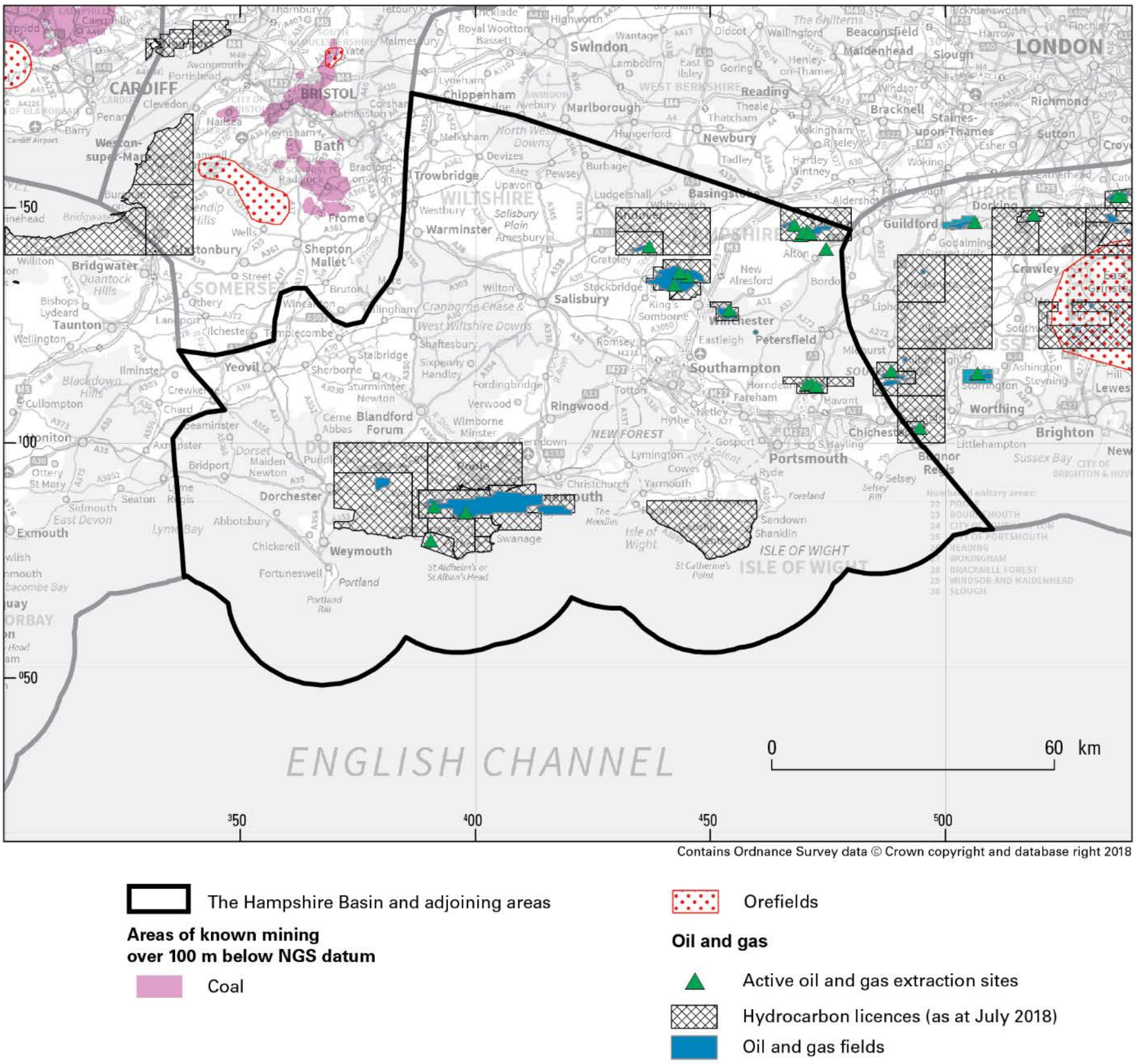
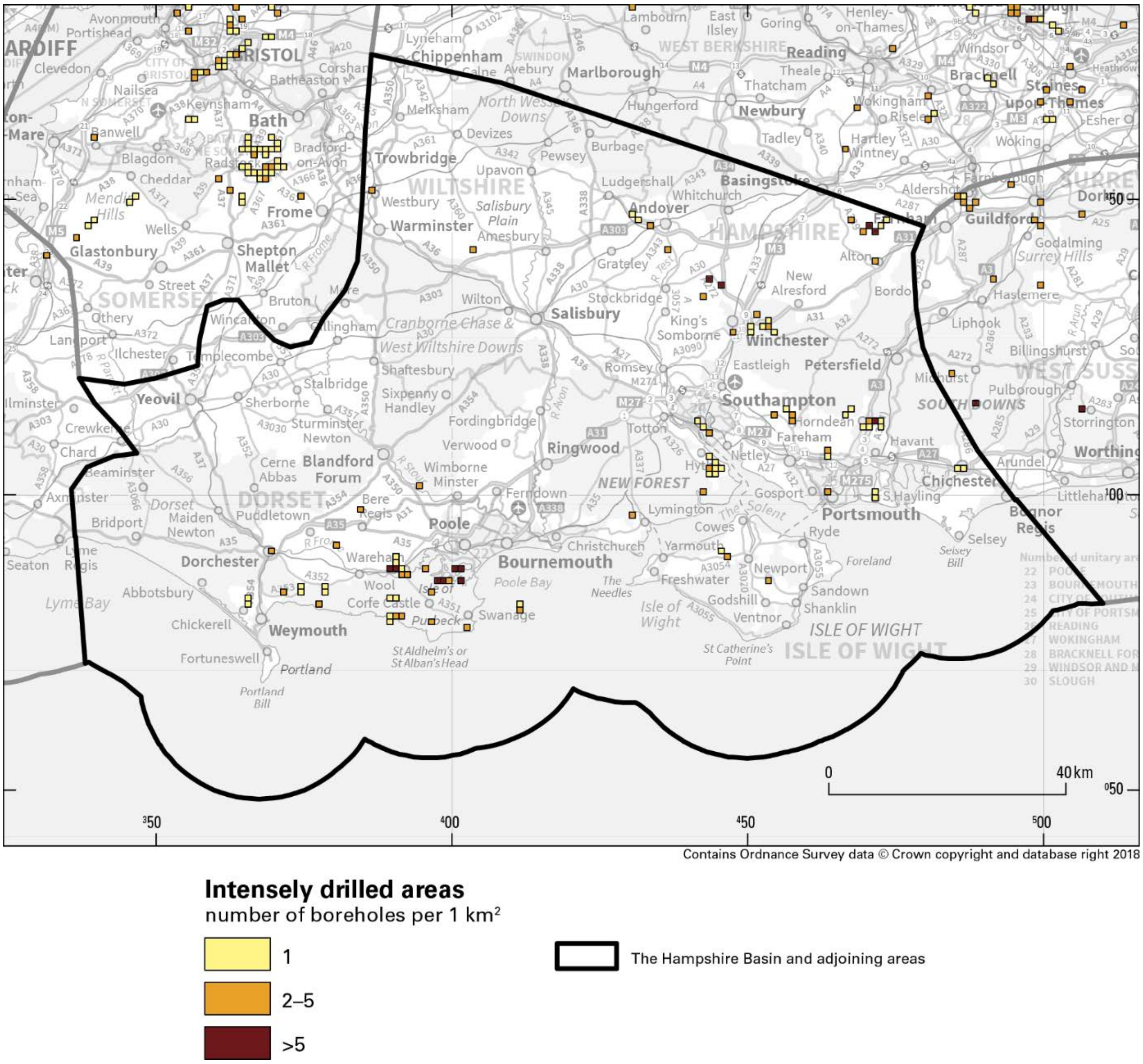


Figure 22 Distribution of mineral resources in the Hampshire region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields 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.



Contains Ordnance Survey data © Crown copyright and database right 2018

Figure 23 Location of intensely drilled areas in the Hampshire region, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

8.11 SUPPORTING INFORMATION

8.11.1 Potash, halite, gypsum/anhydrite and polyhalite deposits

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

8.11.2 Hydrocarbons (oil and gas)

The hydrocarbon fields displayed on Figure 22 are provided by the hydrocarbon industry to the Oil and Gas Authority. They represent the extent of known hydrocarbon resources usually shown by the oil or gas contact with water within the hydrocarbon trap structure.

The hydrocarbon licence areas displayed on Figure 22 represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place.

The approach adopted for exploration and the detailed evaluation of hydrocarbon resources prior to and during exploitation has resulted in the location, extent and depth of conventional hydrocarbon reservoirs being very well constrained. Conversely, the extents, depths and contained resource of unconventional (shale) gas and oil deposits is less well constrained. The distribution of the prospective rock types is based on geological factors 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.

8.11.3 Borehole depths

Not all boreholes are drilled vertically. Some are inclined and others, mainly for hydrocarbon exploitation, are deviated, sometimes with multiple boreholes branching from a single initial borehole. The boreholes 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').

References

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

Glossary, introduction and background

DECC. 2014. Implementing Geological Disposal. A framework for the long-term management of higher activity radioactive waste. URN 14D/235

Environment Agency. 2013. *Groundwater protection: principles and practice* (GP3). Version 1.1, August 2013. (Bristol: Environment Agency.)

Radioactive Waste Management. 2016a. National Geological Screening Guidance: Implementing Geological Disposal: Providing information on geology.

Radioactive Waste Management. 2016b. Geological Disposal. National Geological Screening — Detailed Technical Instructions and Protocols. *RWM Technical Note,* No. 24600903.

Waters, C N, Terrington, R, Cooper, M R, Raine, R B, and Thorpe, S. 2015. The construction of a bedrock geology model for the UK: UK3D_v2015. *British Geological Survey Open Report,* OR/15/069.

Younger, P L, 2007. Groundwater in the environment: an introduction. (Singapore: Blackwell Publishing Ltd.)

Region and rock type

Andrews, I J. 2014. The Jurassic shales of the Weald basin: geology and shale oil and shale gas resource estimation. BGS and DECC.

Barron, A J M, Lott, G K, and Riding, J B. 2012. Stratigraphical framework for the Middle Jurassic strata of Great Britain and the adjoining continental shelf. *British Geological Survey Research Report,* RR/11/06.

Barton, C M, Woods, M A, Bristow, C R, Newell, A J, Westhead, R K, Evans, D J, Kirby, G A, Warrington, G, Riding, J B, Freshney, E C, Highley, D E, Lott, G K, Forster, A, and Gibson, A D. 2011. Geology of south Dorset and south-east Devon and its World Heritage Coast. *Special memoir of the British Geological Survey,* Sheets 328, 341, 342 and 343, part 326, 327, 329, 339 and 340 (England and Wales).

Bristow, C R, Freshney, E C, Penn, I E, Graham, D K, Harland, R, Hughes, M J, Wood, C J, Williams, B J, and Monkhouse, R A. 1990. Geology of the country around Bournemouth. *Memoir of the British Geological Survey,* Sheet 329 (England and Wales).

Bristow, C R, Barton, C M, Freshney, E C, Wood, C J, Evans, D J, Cox, B M, Taylor, R T, Graham, D K, Owen, H G, Wilkinson, I P, Woods, M A, Allen, P M, Lott, G K, Lewis, M E, Cornwell, J D, Royles, C P, Self, S J, Gostelow, T P, and Ivimey-Cook, H C. 1995. Geology of the country around Shaftesbury. *Memoir of the British Geological Survey,* Sheet 313 (England and Wales).

Bristow, C R, Barton, C M, Westhead, R K, Freshney, E C, Cox, B M, Woods, M A, Donovan, D T, Ivimey-Cook, H C, Lott, G K, Riding, J B, Wilkinson, I P, Evans, D J, Kirby, G A, Ball, T K, Cornwell, J D, Chacksfield, B C, and Cheney, C S. 1999. The Wincanton district: a concise account of the geology. *Memoir of the British Geological Survey,* Sheet 297 (England and Wales).

Chadwick, R A. 1986. Extension tectonics in the Wessex Basin, southern England. *Journal of the Geological Society of London,* Vol. 143, 465–488.

Chadwick, R A. 1993. Aspects of basin inversion in southern Britain. *Journal of the Geological Society of London*, Vol. 150, 311–322.

Chadwick, R A, and Evans, D J. 2005. A seismic atlas of southern Britain: images of subsurface structure. *British Geological Survey Occasional Publication,* No. 7.

CHADWICK, R A, KENOLTY, N, and WHITTAKER, A. 1983. Crustal structure beneath southern England from deep seismic reflection profiles. *Journal of the Geological Society of London*, Vol. 140, 893–911.

COX, B M, and GALLOIS, R W. 1981. *The stratigraphy of the Kimmeridge Clay of the Dorset type area and its correlation with some other Kimmeridgian sequences*. (London: HMSO.)

COX, B M, and SUMBLER, M G. 2002. British Middle Jurassic stratigraphy. *Geological Conservation Review Series*, Vol. 26. (Peterborough: Joint Nature Conservation Committee.)

COX, B M, SUMBLER, M G, and IVIMEY-COOK, H C. 1999. A formational framework for the Lower Jurassic of England and Wales (onshore area). *British Geological Survey Research Report*, RR/99/01.

DUFF, P M D and KENYON-SMITH, A. 1992. *Geology of England and Wales*. (London: The Geological Society.)

EVANS, D J, KIRBY, G, and HULBERT, A. 2011. New insights into the structure and evolution of the Isle of Wight Monocline. *Proceedings of the Geologists' Association*, Vol. 122(5), 764–780.

FRESHNEY, E C. 1987. Geology of the country around Southampton. *Memoir of the British Geological Survey*, Sheet 315 (England and Wales).

HALLSWORTH, C R, and KNOX, R W O'B. 1999. BGS Rock Classification Scheme Volume 3: classification of sediments and sedimentary rocks. *British Geological Survey Research Report*, RR/99/03

HAMBLIN, R J O. 1992. *The geology of the English Channel.* (London: HMSO.)

HOPSON, P M. 2011. The geological history of the Isle of Wight: an overview of the 'diamond in Britain's geological crown'. *Proceedings of the Geologists' Association*, Vol. 122, 745–763.

HOPSON, P M, WILKINSON, I P, and WOODS, M A. 2008. A stratigraphical framework for the Lower Cretaceous of England. *British Geological Survey Research Report*, RR/08/03.

HOWARD, A S, WARRINGTON, G, AMBROSE, K, AND REES, J G. 2008. A formational framework for the Mercia mudstone group (Triassic) of England and Wales. *British Geological Survey Research Report*, RR/08/04.

MELVILLE, R V and FRESHNEY, E C (editors). 1982. *British Regional Geology: The Hampshire Basin and adjoining areas*. Fourth edition. (Keyworth, Nottingham: British Geological Survey**.**)

MORGANS-BELL, H S. 2001. Integrated stratigraphy of the Kimmeridge Clay Formation (Upper Jurassic) based on exposures and boreholes in south Dorset. *Geological Magazine*, Vol. 138, 511–539.

PHARAOH, T, AND HASLAM, R . 2018. National Geological Screening Appendix A: structural evolution of the British Isles: an overview. *British Geological Survey Commissioned Report*, CR/17/104.

RHYS, G H, LOTT, G K, and CALVER, M A. 1982. The Winterborne Kingston borehole, Dorset, England, *Report of the Institute of Geological Sciences*, No. 81/3.

WATERS, C N, TERRINGTON, R, COOPER, M R, RAINE, R B, and THORPE, S. The construction of a bedrock geology model for the UK: UK3D_v2015. *British Geological Survey Open Report*, OR/15/069.

WHITTAKER, A. 1980. Shrewton No. 1: geological well completion report. *Institute of Geological Sciences Deep Geology Unit*, Report 80/1.

WHITTAKER, A (editor). 1985. *Atlas of onshore sedimentary basins in England and Wales: post-Carboniferous tectonics and stratigraphy*. (Glasgow: Blackie for the British Geological Survey.)

WHITTAKER, A, CHADWICK, R A, KIRBY, G A, KUBALA, M, PENN, I E, SOBEY, R A, BURGESS, W G, FRESHNEY, E C, and HARRISON, R K. 1980. Marchwood No. 1: geological well completion report. *Institute of Geological Sciences Deep Geology Unit*, Report 80/5.

WHITTAKER, A, HOLLIDAY, D W, and PENN, I E. 1985. *Geophysical logs in British stratigraphy*. (Oxford: Blackwell Scientific.)

WRIGHT, J K, and COX, B M. 2001. British Upper Jurassic stratigraphy (Oxfordian to Kimmeridgian), *Geological Conservation Review Series*, No. 21. (Peterborough: Joint Nature Conservation Committee.)

Structure

ALDISS, D T. 2013. Under-representation of faults on geological maps of the London region: reasons, consequences and solutions. *Proceedings of the Geologists' Association*, Vol. 124, 929–994.

BARTON, C, EVANS, D J, BRISTOW, C, FRESHNEY, E, and KIRBY, G. 1998. Reactivation of relay ramps and structural evolution of the Mere Fault and Wardour Monocline, northern Wessex Basin. *Geological Magazine,* Vol. 135(03), 383–395.

BARTON, C M, WOODS, M A, BRISTOW, C R, NEWELL, A J, WESTHEAD, R K, EVANS, D J, KIRBY, G A, WARRINGTON, G, RIDING, J B, FRESHNEY, E C, HIGHLEY, D E, LOTT, G K, FORSTER, A, and GIBSON, A D. 2011. Geology of south Dorset and south-east Devon and its World Heritage Coast. *Special memoir of the British Geological Survey,* Sheets 328, 341, 342 and 343, part 326, 327, 329, 339 and 340 (England and Wales).

BOOTH, K A, FARRANT, A R, HOPSON, P M, WOODS, M A, EVANS, D J, and WILKINSON, I. 2008. Geology of the Winchester district. *Sheet description of the British Geological Survey,* Sheet 299. (England and Wales.)

BRISTOW, C R, BARTON, C M, FRESHNEY, E C, WOOD, C J, EVANS, D J, COX, B M, IVIMEY-COOK, H C, AND TAYLOR, R T. 1995. Geology of the country around Shaftesbury. *Memoir of the British Geological Survey,* Sheet 313 (England and Wales.)

BRISTOW, C R, BARTON, C M, WESTHEAD, R K, FRESHNEY, E C, COX, B M, AND WOODS, M A. 1999. The Wincanton district: a concise account of the geology. *Memoir of the British Geological Survey,* Sheet 297 (England and Wales.)

BRISTOW, C, FRESHNEY, E, and PENN, I. 1991. Geology of the country around Bournemouth. *Memoir of the British Geological Survey,* Sheet 329 (England and Wales).

CHADWICK, R A. 1986. Extension tectonics in the Wessex Basin, southern England. *Journal of the Geological Society of London,* Vol. 143(3), 465–488.

CHADWICK, R A. 1993. Aspects of basin inversion in southern Britain. *Journal of the Geological Society of London,* Vol. 150(2), 311–322.

CHADWICK, R A, and EVANS, D J. 2005. A seismic atlas of southern Britain: images of subsurface structure. *British Geological Survey Occasional Publication,* No. 7.

CHADWICK, R A, KENOLTY, N, and WHITTAKER, A. 1983. Crustal structure beneath southern England from deep seismic reflection profiles. *Journal of the Geological Society of London,* Vol. 140(6), 893–911.

CHADWICK, R A, PHARAOH, T, and SMITH, N. 1989. Lower crustal heterogeneity beneath Britain from deep seismic reflection data. *Journal of the Geological Society of London,* Vol. 146(4), 617–630.

EVANS, D J, KIRBY, G, and HULBERT, A. 2011. New insights into the structure and evolution of the Isle of Wight Monocline. *Proceedings of the Geologists' Association,* Vol. 122(5), 764–780.

FARRANT, A R, HOPSON, P M, BRISTOW, C R, WESTHEAD, R K, WOODS, M A, EVANS, D J, WILKINSON, I P, and PEDLEY, A. 2011. Geology of Alresford district. *Sheet Description of the British Geological Survey,* Sheet 300 (England and Wales.)

HAMBLIN, R J O, CROSBY, A, BALSON, P S, JONES, S M, CHADWICK, R A, PENN, I E, and ARTHUR, M J. 1992. *United Kingdom offshore regional report: the geology of the English Channel.* (London: HMSO for the British Geological Survey.)

HARVEY, M J, and STEWART, S A. 1998. Influence of salt on the structural evolution of the Channel basin. *Geological Society of London Special Publications,* No. 133, 241–266.

HAWKES, P W, FRASER, A J, and EINCHCOMB, C C G. 1998. The tectono-stratigraphic development and exploration history of the Weald and Wessex Basins, southern England, UK. *Geological Society of London Special Publications,* 133(1), 39–65.

HOPSON, P M. 1999. Geology of the Fareham and Portsmouth district. *Sheet Description of the British Geological Survey,* Sheet 316 and part of 331 (England and Wales).

LAKE, S D, and KARNER, G D. 1987. The structure and evolution of the Wessex Basin, southern England: an example of inversion tectonics. *Tectonophysics*, Vol. 137(1), 347–378.

LEE, M, PHARAOH, T, and SOPER, N, 1990. Structural trends in central Britain from images of gravity and aeromagnetic fields. *Journal of the Geological Society of London*, Vol. 147(2), 241–258.

LEE, M, PHARAOH, T, and GREEN, C. 1991. Structural trends in the concealed basement of eastern England from images of regional potential field data. *Annales de la Société Géologique de Belgique*, Vol. 114, 45–62.

MANSY, J-L, MANBY, G, AVERBUCH, O, EVERAERTS, M, BERGERAT, F, VAN VLIET-LANOE, B, LAMARCHE, J, and VANDYCKE, S. 2003. Dynamics and inversion of the Mesozoic basin of the Weald–Boulonnais area: role of basement reactivation. *Tectonophysics*, Vol. 373(1), 161–179.

MILIORIZOS, M., and RUFFELL, A. 1998. Kinematics of the Watchet–Cothelstone–Hatch fault system: implications for the fault history of the Wessex Basin and adjacent areas. 311–330 in *Development, Evolution and Petroleum Geology of the Wessex Basin*. UNDERHILL, J R (editor), *Geological Society of London Special Publications*, 133.

MORTIMORE, R. 2011. Structural geology of the Upper Cretaceous Chalk Central Mass, Isle of Wight, UK. *Proceedings of the Geologists' Association*, Vol. 122(2), 298–331.

NOWELL, D. 1995. Faults in the Purbeck–Isle of Wight monocline. *Proceedings of the Geologists' Association*, Vol. 106(2), 145–150.

OSBORNE WHITE, H J. 1912. Geology of the country around Winchester and Stockbridge. (London: HMSO.)

PARRISH, R R, PARRISH, C M and LASALLE, S. 2018. Vein calcite dating reveals Pyrenean orogen as cause of Paleogene deformation in southern England. *Journal of the Geological Society of London*, Vol. 175(3), 425–442.

PEACOCK, D. 2009. A review of Alpine deformation and stresses in southern England. *Bollettino della Societa Geologica Italiana*, Vol. 128(2), 307–316.

PHARAOH, T, AND HASLAM, R . 2018. National Geological Screening Appendix A: structural evolution of the British Isles: an overview. *British Geological Survey Commissioned Report*, CR/17/104.

PRODDEN, H. 2005. Strike-slip faulting in Somerset and adjacent areas. *Geoscience in South West England*, Vol. 11(2), p. 158.

SMITH, N, KIRBY, G, and PHARAOH, T C. 2005. Structure and evolution of the south-west Pennine basin and adjacent areas. *Subsurface memoir of the British Geological Survey*.

STONELEY, R. 1982. The structural development of the Wessex Basin. *Journal of the Geological Society of London*, Vol. 139(4), 543–554.

WHITE, H J O. 1921. A short account of the geology of the Isle of Wight. (London: HMSO.)

WHITTAKER, A. 1985. *Atlas of onshore sedimentary basins in England and Wales: post-Carboniferous tectonics and stratigraphy.* (Glasgow: Blackie.)

WILSON, V, WELCH, F B A, ROBBIE, J E, and GREEN, G W. 1958. Geology of the country around Bridport and Yeovil. *Memoir of the British Geological Survey*, Sheet 327 and 312 (England and Wales).

Groundwater

ALEXANDER, J. 1983. The groundwater regime of the Harwell region. *Institute of Geological Sciences Report* No. FLPU 83-10.

ALLEN, D J, BREWERTON, L J, COLEBY, L M, GIBBS, B R, LEWIS, M A, MACDONALD, A M, WAGSTAFF, S J, and WILLIAMS, A T. 1997. The physical properties of major aquifers in England and Wales. *British Geological Survey Technical Report*, WD/97/034; *Environment Agency R&D Publication*, No. 8.

ATKINSON, T C, and SMITH, D I. 1974. Rapid groundwater flow in fissures in the chalk: an example from south Hampshire. *Quarterly Journal of Engineering Geology*, Vol. 7(2), 197–205.

BARTON, C M, HOPSON, P M, NEWELL, A J, and ROYSE, K R. 2003, Geology of the Ringwood district. *Sheet Explanation of the British Geological Survey*, Sheet 314 Ringwood (England and Wales.)

BRISTOW, C R, FRESHNEY, E C, and PENN, I E. 1991. Geology of the country around Bournemouth. *Memoir of the British Geological Survey,* Sheet 329 (England and Wales).

BRISTOW, C R, BARTON, C M, FRESHNEY, E C, WOOD, C J, EVANS, D J, COX, B M, IVIMEY-COOK, H C, and TAYLOR, R T. 1995. Geology of the country around Shaftesbury. *Memoir of the British Geological Survey,* Sheet 313 (England and Wales).

BRISTOW, C R, BARTON, C M, WESTHEAD, R K, FRESHNEY, E C, COX, B M, and WOODS, M A. 1999. The Wincanton district — a concise account of the geology. *Memoir of the British Geological Survey,* Sheet 297 (England and Wales).

BURLEY, A J, EDMUNDS, W M, and GALE, I N, 1984. Investigation of the geothermal potential of the UK: catalogue of geothermal data for the land area of the United Kingdom. Second revision. *British Geological Survey Technical Report,* WJ/GE/84/020.

CHINSMAN, W E. 1972. Field and laboratory studies of 'short-term' earthworks failures involving the Gault Clay in West Kent. Unpublished PhD thesis. University of Surrey.

COX, B M, and GALLOIS, R W. 1981. The stratigraphy of the Kimmeridge Clay of the Dorset type area and its correlation with some other Kimmeridgian sequences. (London: HMSO.)

COX, B M, and SUMBLER, M G. 2002. British Middle Jurassic stratigraphy. *Geological Conservation Review Series,* Vol. 26. (Peterborough: Joint Nature Conservation Committee.)

DARLING, W G, EDMUNDS, W M, and SMEDLEY, P L. 1997. Isotopic evidence for palaeowaters in the British Isles. *Applied Geochemistry,* Vol. 12, 813–829.

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

EDMUNDS, W M, DOHERTY, P, GRIFFITHS, K, SHAND, P, and PEACH, D. 2002. Baseline report series 4: the Chalk of Dorset. *British Geological Survey and Environment Agency,* CR/02/268N.

EDWARDS, R A, and FRESHNEY, E C. 1987. Geology of the country around Southampton. *Memoir of the British Geological Survey,* Sheet 315 (England and Wales).

ENVIRONMENT AGENCY. 2013. Groundwater protection: principles and practice (GP3). Version 1.1. (Bristol: Environment Agency.)

EUROPEAN UNION. 2000. Water Framework Directive: directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. *Official Journal of the European Union,* OJL327, 1–73.

FARRANT, A R, HOPSON, P M, BRISTOW, C R, WESTHEAD, R K, WOODS, M A, EVANS, D J, WILKINSON, I and PEDLEY, A. 2011. Geology of Alresford district. *Sheet description of the British Geological Survey,* Sheet 300 (England and Wales).

FORSTER, A, HOBBS, P R N, CRIPPS, A C, ENTWISLE, D C, FENWICK, S M M, RAINES, M R, HALLAM, J R, JONES L D, SELF S J and MEAKIN J L, 1994. Engineering geology of British rocks and soils: Gault Clay. *British Geological Survey Technical Report,* WN/94/031.

FREEZE, A R, AND CHERRY, J A. 1979. Groundwater. (New Jersey, USA: Prentice Hall.)

HOBBS, P, HALLAM, J R, FORSTER, A, ENTWISLE, D, JONES, L D, CRIPPS, A C, NORTHMORE, K J, SELF, S and MEAKIN, J L. 2002. Engineering geology of British rocks and soils: mudstones of the Mercia Mudstone Group. *British Geological Survey Research Report,* RR/01/002, 106pp

HOPSON, P M. 1999. Geology of the Fareham and Portsmouth district. *Sheet Description of the British Geological Survey,* Sheet 316 and part of 331 (England and Wales).

HOPSON, P M. 2008. Geology of the Salisbury district. *Sheet Description of the British Geological Survey,* Sheet 298 (England and Wales).

HOPSON, P M, and FARRANT, A R. 2015, Geology of the Isle of Wight. *Sheet Explanation of the British Geological Survey,* parts of Sheets 330, 331, 344 and 345 (England and Wales).

INSTITUTE OF GEOLOGICAL SCIENCES and SOUTHERN WATER AUTHORITY, 1979. Hydrogeological map of the Hampshire and the Isle of Wight. *British Geological Survey Hydrogeological Maps of the United Kingdom,* Sheet 9.

INSTITUTE OF GEOLOGICAL SCIENCES and WESSEX WATER AUTHORITY, 1979. Hydrogeological map of the Chalk and associated minor aquifers of Wessex. *British Geological Survey Hydrogeological Maps of the United Kingdom,* Sheet 8.

JONES, H K, MORRIS, B L, CHENEY, C S, BREWERTON, L J, MERRIN, P D, LEWIS, M A, MACDONALD, A M, COLEBY, L M, TALBOT, J C, MCKENZIE, A A, BIRD, M J, CUNNINGHAM, J E, and ROBINSON, V. 2000. The physical properties of minor aquifers in England and Wales. *British Geological Survey Technical Report,* WD/00/04*: Environment Agency R&D Publication,* No. 68.

MELVILLE, R V and FRESHNEY, E C (editors). 1982. *British Regional Geology: the Hampshire Basin and adjoining areas.* Fourth edition. (Keyworth, Nottingham: British Geological Survey.**)**

OSBORNE WHITE, H J. 1913. The geology of the country around Fareham and Havant. *Memoir of the Geological Survey,* Sheet 316 (England and Wales).

OSBORNE WHITE, H J. 1923. The geology of the country south and west of Shaftesbury. *Memoir of the Geological Survey,* Sheet 313 (England and Wales).

RHYS, G H, LOTT, G K, and CALVER, M A. 1982. The Winterborne Kingston borehole, Dorset, England, *Report of the Institute of Geological Sciences,* No. 81/3.

SHAND, P, COBBING, J, TYLER-WHITTLE, R, TOOTH, A F, and LANCASTER, A. 2003. Baseline report series 9: the Lower Greensand of southern England. *British Geological Survey Commissioned Report and Environment Agency*, CR/03/273N.

SHAND, P, ANDER, E L, GRIFFITHS, K, DOHERTY, P, and LAWRENCE, A R. 2004. Baseline report series 11: the Bridport sands of Dorset and Somerset. *British Geological Survey Commissioned Report and Environment Agency*, CR/04/166N.

STUART, M E, and SMEDLEY, P L. 2009. Baseline groundwater chemistry: the Chalk aquifer of Hampshire. *British Geological Survey Open Report,* OR/09/052.

WALTHAM, A C, SIMMS, M J, FARRANT, A R, and GOLDIE, H S. 1997. *Karst and caves of Great Britain,* (Chapman and Hall.)

WHITAKER, W. 1910. The water supply of Hampshire (including the Isle of Wight), with records of sinkings and borings. *Memoir of Geological Survey* (England and Wales).

WRIGHT, J K, and COX, B M. 2001. British Upper Jurassic stratigraphy (Oxfordian to Kimmeridgian), *Geological Conservation Review Series,* No. 21. (Peterborough: Joint Nature Conservation Committee.)

Natural processes

ADAMS, J. 1996. Paleoseismology in Canada: a dozen years of progress. *Journal of Geophysical Research,* Vol. 101, 6193–6207.

AMANTE, C, and EAKINS, B. 2009. ETOPO1 1Arc-Minute Global Relief Model: procedures, data resources and analysis. *National Geophysical Data Centre, NOAA Technical Memorandum NESDIS NGDC,* No 24.

AMBRASEYS, N, and JACKSON, D. 1985. Long-term seismicity in Britain. 49–66 in *Earthquake engineering in Britain*. (London: Thomas Telford.)

BAPTIE, B. 2010. State of stress in the UK from observations of local seismicity. *Tectonophysics,* Vol. 482, 150–159.

BAPTIE, B. 2012. UK earthquake monitoring 2011/2012: Twenty-third Annual Report. *British Geological Survey Open Report,* OR/12/092.

BOLT, B A, and ABRAHAMSON, N A. 2003. Estimation of strong seismic ground motions. 983–1001 in *International Handbook of Earthquake and Engineering Seismology*. LEE, W H K, KANAMORI, H, JENNINGS, P C, and KISSLINGER, C (editors). (San Diego: Academic Press.)

BUSBY, J P, KENDER, S, WILLIAMSON, J P, and LEE, J R. 2014. Regional modelling of the potential for permafrost development in Great Britain. *British Geological Survey Commissioned Report,* CR/14/023.

CAMELBEECK, T. 1999. The potential for large earthquakes in regions of present day low seismic activity in Europe. *Proceedings of the 9th Conference on Soil Dynamics and Earthquake Engineering,* Bergen, 9 to 12th August, 1999.

CAMELBEECK, T, and MEGHRAOUI, M. 1996. Large earthquakes in northern Europe more likely than once thought. *EOS,* Vol. 77, 405–409.

CHADWICK, R A, PHARAOH, T C, WILLIAMSON, J P, and MUSSON, R M W. 1996. Seismotectonics of the UK. *British Geological Survey Technical Report,* WA/96/3C.

CLARK, C D, GIBBARD, P L, and ROSE, J. 2004. Pleistocene glacial limits in England, Scotland and Wales. 47–82 in *Quaternary glaciations extent and chronology Part 1: Europe*. EHLERS, J, and GIBBARD, P L (editors). (Amsterdam: Elsevier.)

CLARK, C D, HUGHES, A L, GREENWOOD, S L, JORDAN, C, and SEJRUP, H P. 2012. Pattern and timing of retreat of the last British–Irish ice sheet. *Quaternary Science Reviews,* Vol. 44, 112–146.

DAVENPORT, C, RINGROSE, P, BECKER, A, HANCOCK, P, and FENTON, C. 1989. Geological investigations of late and postglacial earthquake activity in Scotland. 175–194 in *Earthquakes at North Atlantic passive margins: neotectonics and postglacial rebound*. GREGERSEN, S, and BASHAM, P (editors). (Dordrecht: Kluwer.)

DEICHMANN, N. 2006. Local magnitude, a moment revisited. *Bulletin of the Seismological Society of America,* Vol. 96, 1267–1277.

FIRTH, C, and STEWART, I. 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. *Quaternary Science Reviews,* Vol. 19, 1469–1493.

FRENCH, H M. 2007. *The periglacial environment.* (Wiley.)

GALLOWAY, D, BUKITS, J, and FORD, G. 2013. Bulletin of British Earthquakes 2012. *British Geological Survey Seismological Report,* OR/13/54.

GIARDINI, D, WOESSNER, J, DANCIU, L, CROWLEY, H, COTTON, F, GRÜNTHAL, G, PINHO, R, VALENSISE, G, AKKAR, S, ARVIDSSON, R, BASILI, R, CAMEELBEECK, T, CAMPOS-COSTA, A, DOUGLAS, J, DEMIRCIOGLU, M, ERDIK, M, FONSECA, J, GLAVATOVIC, B, LINDHOLM, C, MAKROPOULOS, K, MELETTI, C, MUSSON, R, PITILAKIS, K, SESETYAN, K, STROMEYER, D, STUCCHI, M, and ROVIDA, A. 2013. A seismic hazard harmonisation in Europe (SHARE): online data resource. doi: 10.12686/SED-00000001-SHARE

GRÜNTHAL, G, and WAHLSTRÖM, R. 2012. The European–Mediterranean Earthquake Catalogue (EMEC) for the last millennium. *Journal of Seismology,* Vol. 16, 535–570.

GRÜNTHAL, G, WAHLSTRÖM, R, and STROMEYER, D. 2009. The unified catalogue of earthquakes in central, northern, and north-western Europe (CENEC) updated and expanded to the last millennium. *Journal of Seismology,* Vol. 13, 517–541.

GUTENBERG, B, and RICHTER, C F. 1954. Seismicity of the Earth and associated phenomena. (Princeton, New Jersey: Princeton University Press.)

JOHNSTON, A C, COPPERSMITH, K J, KANTER, L R, and CORNELL, C A. 1994. The earthquakes of stable continental regions. *Electric Power Research Institute,* TR-102261-V4. (Palo Alto)

LAGERBÄCK, R. 1979. Neotectonic structures in Northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar,* Vol. 112, 333–354.

LEE, J R, ROSE, J, HAMBLIN, R J, MOORLOCK, B S, RIDING, J B, PHILLIPS, E, BARENDREGT, R W, and CANDY, I. 2011. The glacial history of the British Isles during the Early and Mid Pleistocene: implications for the long-term development of the British ice sheet. 59–74 in *Quaternary glaciations — extent and chronology, a closer look.* Developments in Quaternary Science. 15. EHLERS, J, GIBBARD, P L, and HUGHES, P D (editors). (Amsterdam: Elsevier.)

LOUTRE, M F, and BERGER, A. 2000. Future climate changes: are we entering and exceptionally long interglacial. *Climate Change,* Vol. 46, 61–90.

LUND, B. 2005. Effects of deglaciation on the crustal stress field and implications for end-glacial faulting: a parametric study for simple Earth and ice models. *SKB Technical Report*, TR-05-04.

MUSSON, R M W. 1994. A catalogue of British earthquakes. *British Geological Survey Global Seismology Report*, WL/94/04.

MUSSON, R M W. 1996. The seismicity of the British Isles. *Annali di Geofisica*, Vol. 39, 463–469.

MUSSON, R M W. 2004. A critical history of British earthquakes. *Annals of Geophysics*, Vol. 47, 597–610.

MUSSON, R M W. 2007. British earthquakes. *Proceedings of the Geologists' Association*, Vol. 118, 305–337.

MUSSON, R M W, and SARGEANT, S L. 2007. Eurocode 8 seismic hazard zoning maps for the UK. *British Geological Survey Commissioned Report*, CR/07/125.

NEILSON, G, MUSSON, R M W, and BURTON, P W. 1984. Macroseismic reports on historical British earthquakes V: the south and south-west of England. *British Geological Survey Global Seismology Report*, No 231 (Edinburgh).

PASCAL, C, STEWART, I, and VERMEERSEN, B. 2010. Neotectonics, seismicity and stress in glaciated regions. *Journal of Geological Society of London*, Vol. 167, 361–362.

RADIOACTIVE WASTE MANAGEMENT. 2016a. National Geological Screening Guidance: Implementing Geological Disposal: Providing information on geology.

RADIOACTIVE WASTE MANAGEMENT. 2016b. Geological Disposal. National Geological Screening — Detailed Technical Instructions and Protocols. *RWM Technical Note,* No. 24600903.

REITER, L. 1990. *Earthquake hazard analysis*. (New York: Columbia University Press.)

RINGROSE, P, HANCOCK, P, FENTON, C, and DAVENPORT, C. 1991. Quaternary tectonic activity in Scotland. 390–400 in *Quaternary Engineering Geology*. FORSTER, A, CULSHAW, M, CRIPPS, J, LITTLE, J, and MOON, C (editors). *Geological Society of London Engineering Geology Special Publication*, No. 7.

RYDELEK, P, and SACKS, I. 1989. Testing the completeness of earthquake catalogues and the hypothesis of self-similarity. *Nature*, Vol. 337, 251–253.

SARGEANT, S L, and OTTEMÖLLER, L. 2009. Lg wave attenuation in Britain. *Geophysical Journal International*, Vol. 179, 1593–1606.

SHAW, R P, AUTON, C A, BAPTIE, B, BROCKLEHURST, S, DUTTON, M, EVANS, D J, FIELD, L P, GREGORY, S P, HENDERSON, E, HUGHES, A J, MILODOWSKI, A E, PARKES, D, REES, J G, SMALL, J, SMITH, N J P, TYE, A, and WEST, J M. 2012. Potential natural changes and implications for a UK GDF. *British Geological Survey Commissioned Report*, CR/12/127.

STEIN, S S, CLOETINGH, S, SLEEP, N H, and WORTEL, R. 1989. Passive margin earthquakes, stresses and rheology. 231–259 in *Earthquakes at North Atlantic passive margins: neotectonics and postglacial rebound*. GREGERSEN, S, and BASHAM, P W (editors). (Dordrecht: Kluwer.)

STEWART, I, SAUBER, J, and ROSE, J. 2000. Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. *Quaternary Science Review*, Vol. 19(14–15), 1367–1389.

STUCCHI, M, ROVIDA, A, GOMEZ CAPERA, A, ALEXANDRE, P, CAMEELBEECK, T, DEMIRCIOGLU, M, GASPERINI, P, KOUSKOUNA, V, MUSSON, R, RADULIAN, M, SEETYAN, K, VILANOVA, S, BAUMONT, D, BUNGUM, H, FAH, D, LENHARDT, W, MAKROPOULOS, K, MARTINEZ SOLARES, J, SCOTTI, O, ZIVCIC, M, ALBINI, P, BATLLO, J, PAPAIOANNOU, C, TATEVOSSIAN, R, LOCATI, M, MELETTI, C, VIGANO', D, and GIARDINI, D. 2013. The SHARE European Earthquake Catalogue (SHEEC) 1000–1899. *Journal of Seismology*, Vol. 17, 523–544.

TURBITT, T, BARKER, E J, BROWITT, C W A, HOWELLS, M, MARROW, P C, MUSSON, R M W, NEWMARK, R H, REDMAYNE, D W, WALKER, A B, JACOB, A W B, RYAN, E, and WARD, V. 1985. The North Wales earthquake of 19 July 1984. *Journal of the Geological Society of London*, Vol. 142, 567–571.

WOODCOCK, N H, and STRACHAN, R. 2000. *Geological history of Britain and Ireland*. (Oxford, UK: Blackwell Publishing.)

Resources

Borehole locations

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

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/