British Geological Survey
Expert | Impartial | Innovative

National Geological Screening: Bristol and Gloucester region

Minerals and Waste Programme

Commissioned Report CR/17/097

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/097

National Geological Screening: Bristol and Gloucester region

A Farrant[1], D Schofield[1], D E Evans[2], R Haslam[2], S Loveless[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, Bristol and Gloucester, rock type, structure, groundwater, natural processes, resources

Bibliographical reference

FARRANT, A, SCHOFIELD, D, EVANS, D E, HASLAM, R, LOVELESS, S, BLOOMFIELD, J P, LEE, J R, BAPTIE, B, SHAW, R P, BIDE T AND F M MCEVOY. 2018. National Geological Screening: Bristol and Gloucester region. *British Geological Survey Commissioned Report*, CR/17/097. 88pp.

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 Bristol and Gloucester 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 Bristol and Gloucester region (Figure 1).

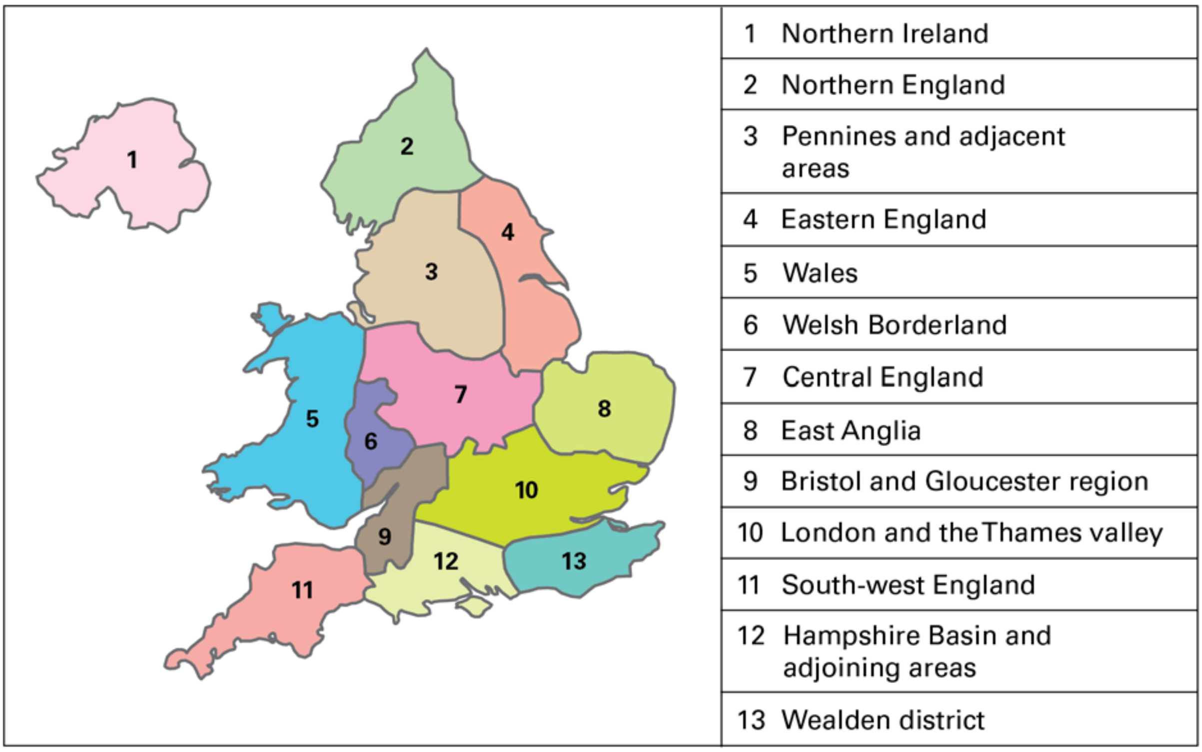


Figure 1 The BGS region boundaries as defined by the Regional Guides series of reports (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html). British Geological Survey © UKRI 2018

2 Background

2.1 NATIONAL GEOLOGICAL SCREENING GUIDANCE

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

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

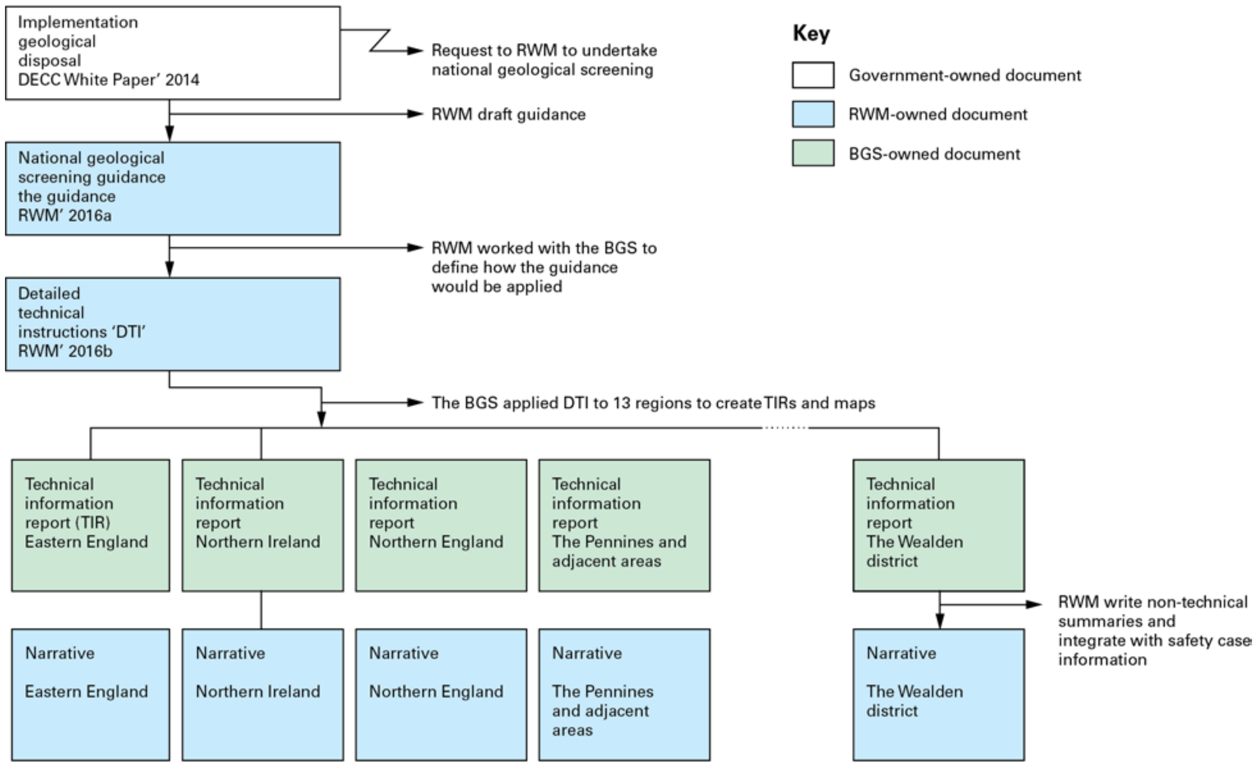


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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

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

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

2.2 DETAILED TECHNICAL INSTRUCTIONS

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

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

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

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

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

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

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

i. **Rock type**

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

ii. **Rock structure**

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

iii. **Groundwater**

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

iv. **Natural processes**

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

v. **Resources**

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

3 The Bristol and Gloucester region

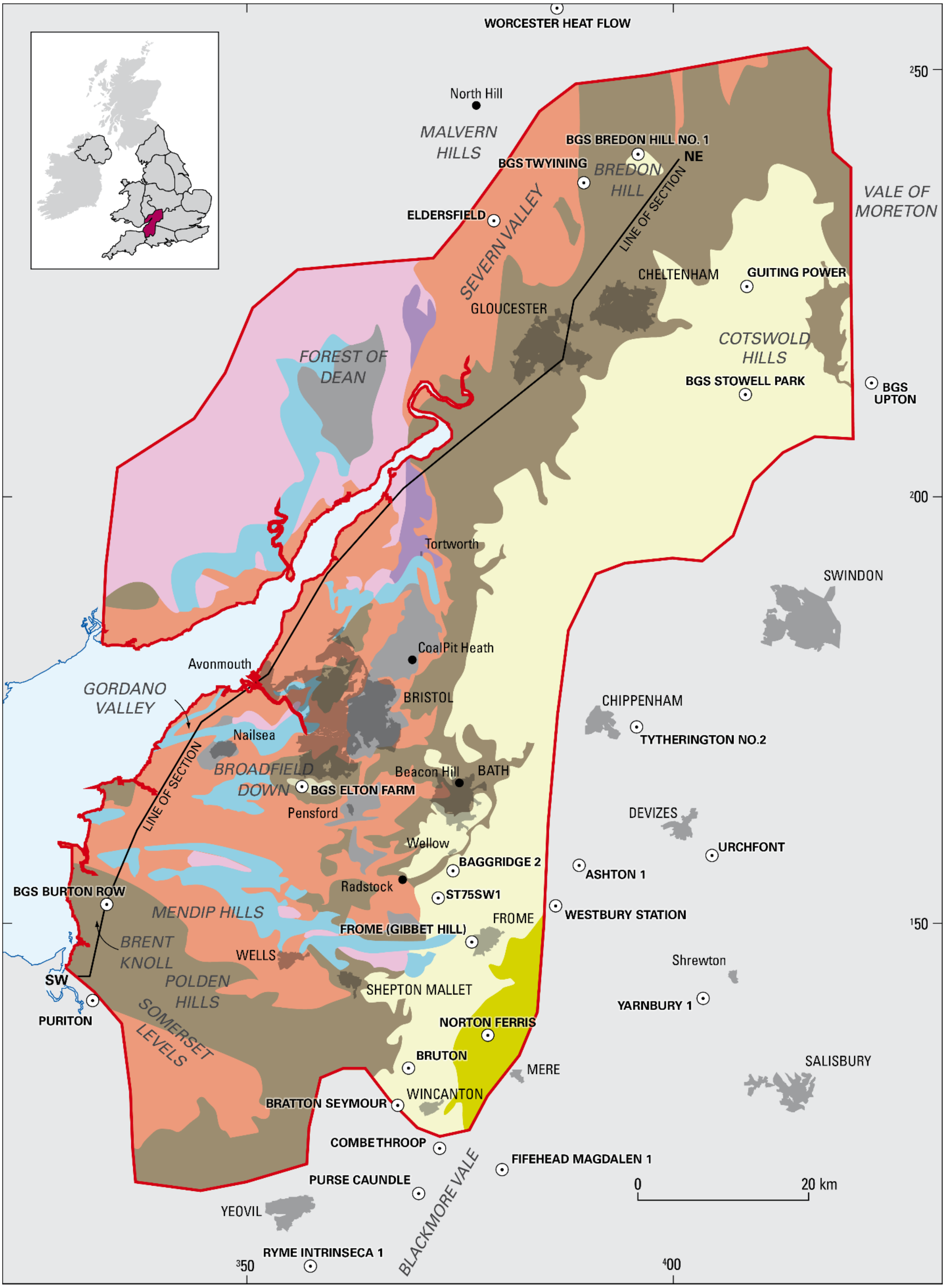
This region covers most of Somerset, Bristol, Bath, south Gloucestershire and the Forest of Dean. The region is one of the most geologically varied parts of the Great Britain, with almost every geological time period represented (Figure 3). The region's diverse landscape reflects the underlying bedrock geology, comprising uplands of harder Palaeozoic limestone, coalfield basins, Jurassic escarpments, low-lying clay plains and coastal flats. This variability is in part due to erosion locally revealing older, deformed Palaeozoic rocks beneath the Mesozoic cover.

The area has a very long history of geological exploration, dating back to production of the world's first geological map, based on the country around Bath. Consequently, there is a significant amount of historical information on the geology of the region. Much of this early research was driven by the exploitation of the region's mineral resources. In addition, the region's diverse geology and landscape provides many natural exposures, particularly for the harder Palaeozoic rocks and Jurassic limestones. These rocks are also often exposed in pits and quarries. Consequently the near-surface geology is well known. At depth, our knowledge comes from mine plans, shafts and boreholes, many of the latter drilled for mineral resources and groundwater. However, with less than 40 boreholes penetrating more than 400 m, and only six beyond 600 m, the deeper geology is less well known. In the far south-east of the region, this information is supplemented by geophysical surveys (seismic, gravity and magnetic) that provide an overview of the rocks and deeper structures. However, the information on the deeper rocks is mostly clustered in areas where there has been exploration for coal, hydrocarbons and mineral salts (evaporites). Consequently, our understanding of the geology of the region is better in some areas than others and, in general, our understanding is less certain at depth.

3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

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

Geologically, the region can be broadly subdivided into several distinct areas (Figure 3). These include: the Worcester basin; the Forest of Dean coalfield; the north Somerset–Bristol coalfield; the Variscan thrust belt, which includes the Mendip Hills, Broadfield Down and the Gordano valley; the Bristol Channel–Somerset basin, including the Somerset Levels and the Polden Hills; the Jurassic scarp and vale topography of the Cotswolds including the southern extension between Shepton Mallet and Yeovil, and the western fringe of the Wessex basin in the far south-east of the region.



WORCESTER HEAT FLOW
North Hill
MALVERN HILLS
BGS BREDON HILL NO. 1
BGS TWYINING
BREDON HILL
NE
LINE OF SECTION
VALE OF MORETON
ELDERSFIELD
SEVERN VALLEY
CHELTENHAM
GUITING POWER
GLOUCESTER
COTSWOLD HILLS
FOREST OF DEAN
BGS STOWELL PARK
BGS UPTON
Tortworth
SWINDON
Coal Pit Heath
Avonmouth
GORDANO VALLEY
BRISTOL
CHIPPENHAM
TYTHERINGTON NO.2
Nailsea
BROADFIELD DOWN
BGS ELTON FARM
Beacon Hill
BATH
Pensford
DEVIZES
Wellow
URCHFONT
BAGGRIDGE 2
ASHTON 1
BGS BURTON ROW
Radstock
ST75SW1
MENDIP HILLS
WESTBURY STATION
FROME
FROME (GIBBET HILL)
BRENT KNOLL
WELLS
POLDEN HILLS
Shrewton
SW
SHEPTON MALLET
YARNBURY 1
PURITON
SOMERSET LEVELS
NORTON FERRIS
BRUTON
MERE
SALISBURY
WINCANTON
BRATTON SEYMOUR
COMBE THROOP
FIFEHEAD MAGDALEN 1
PURSE CAUNDLE
BLACKMORE VALE
YEOVIL
RYME INTRINSECA 1
250
200
150
350
400
0
20 km

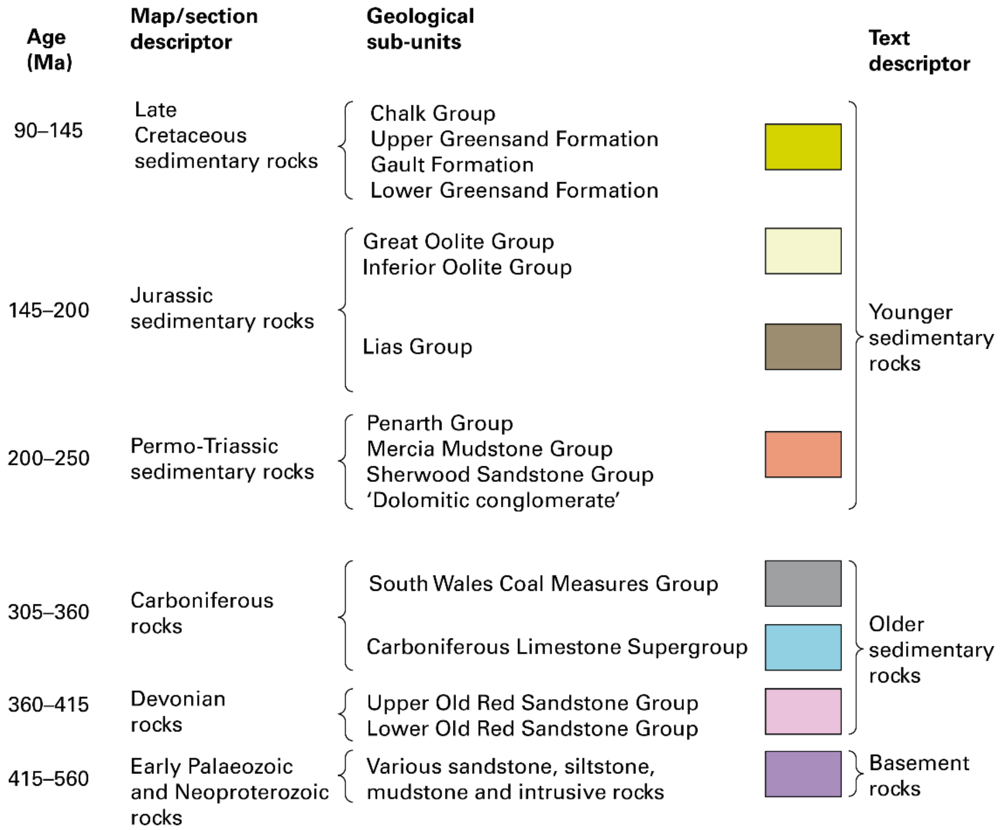


Figure 3 Generalised geological map and key showing the distribution of younger sedimentary rocks, older sedimentary rocks and basement rocks in the onshore Bristol and Gloucester region. The inset map shows the extent of the region in the UK. See Figure 4 for a schematic cross-section. The 'Geological sub units' column is highly generalised and does not represent all geological units in the region. Stratigraphical nomenclature and lithological descriptions are simplified and therefore may differ from those used in other sections of this report. The locations of key boreholes mentioned in the text are shown by a circle and dot. Contains public sector information licenced under the Open Government Licence v3.0. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018

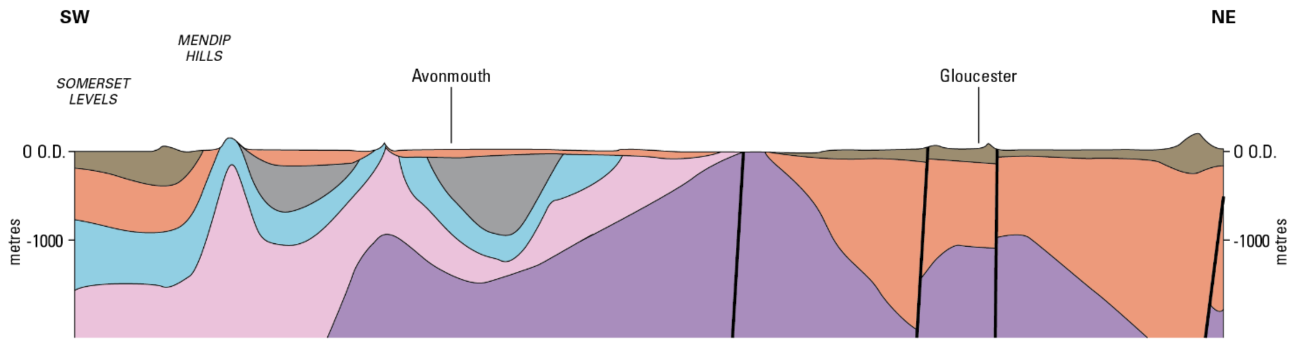


Figure 4 Schematic south-west to north-east cross-section through the Bristol and Gloucester region. Line of section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018

4 Screening topic 1: rock type

4.1 OVERVIEW OF ROCK TYPE APPROACH

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

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

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

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

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

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

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

4.2 POTENTIAL ROCK TYPES OF INTEREST IN THE BRISTOL AND GLOUCESTER REGION

A generalised vertical section (GVS) for the Bristol and Gloucester region is presented in Table 3, 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 Bristol and Gloucester region, the GVS groups the rocks into three age ranges: younger sedimentary rocks (Cretaceous, Jurassic, Triassic and Permian); older sedimentary rocks (Devonian and Carboniferous), and basement rocks (Table 3). The rocks in the region are predominantly sedimentary in origin. Some of the rock units are considered to represent PRTIs present within the depth range of interest, between 200 and 1000 m below NGS datum. These include a number of lower strength sedimentary rock units (LSSR) and an evaporite (EVAP) PRTI in the younger sedimentary rocks as well as higher strength rock (HSR) PRTIs in the older sedimentary and basement rocks.

The thickness, composition and depth of the LSSR PRTIs are dependent on both the original depositional environment, structural activity during deposition and subsequent tectonic deformation. The development of a series of sedimentary basins during the Mesozoic (Figure 5) influenced the deposition of mudstone units across the region. In the north, sedimentation was focused in the Worcester basin, a north–south graben system bounded to the west by the East Malvern Fault (Figure 5), a major normal fault with a downthrow of over 2500 m in places (Chadwick and Evans, 1995), and in the east by the Vale of Moreton axis. Farther south, the presence of a topographical high over the Variscan thrust belt led to reduced or no deposition over the Mendip high and Bristol–Radstock shelf. In the south, deposition was centred in the Bristol Channel basin and its eastward extension through central Somerset into the Wessex basin.

These rocks have locally been affected by relatively minor post-depositional tectonic deformation. Consequently, for each Mesozoic PRTI there are significant changes in sediment facies, thickness and depth profiles across the region. The Late Cretaceous Gault and Kimmeridge Clay formations, PRTIs in other regions, have very limited extent within the Bristol and Gloucester region and are only present at very shallow depths and not within the depth range of interest.

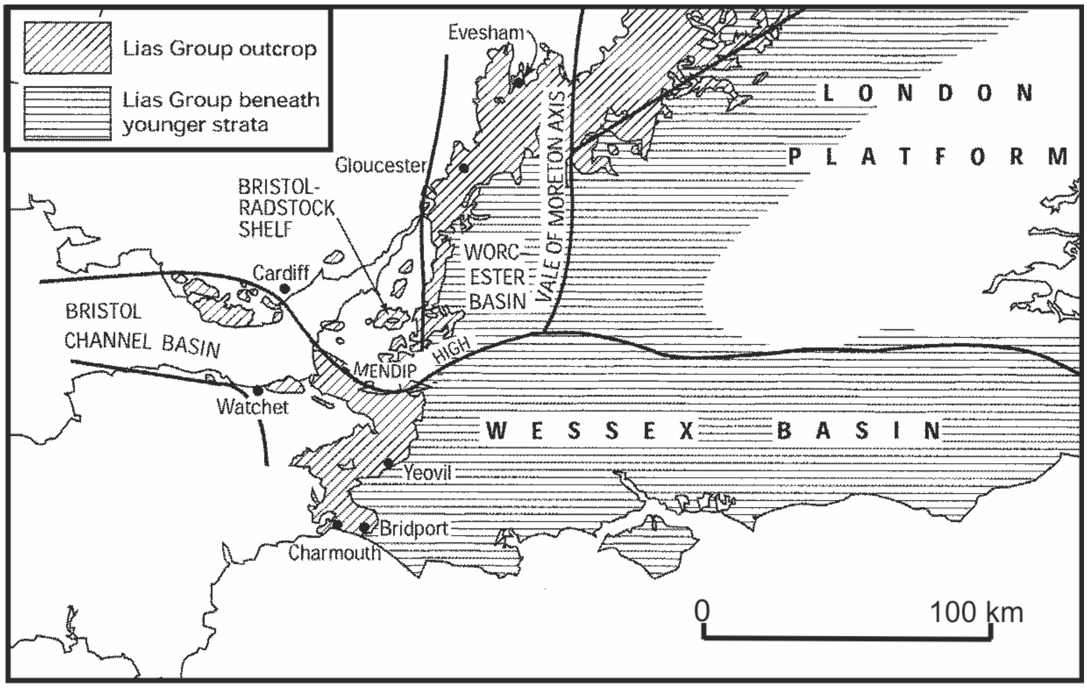


Figure 5 Generalised outcrop map of the Lias Group in England and Wales showing the structural elements that controlled deposition (from Cox et al., 1999). British Geological Survey © UKRI 2018

The majority of the basement rocks in the region, north of a line drawn between Weston-super-Mare to Bath across the region and comprising early Palaeozoic sediments, lie outside the established Variscan cleavage belt of south-west England. It is not known whether the mudstone component of these rocks, proved in boreholes and inferred from geophysical and gravity data, preserves a pervasive cleavage, and therefore is sufficiently compacted and metamorphosed (Table 2). Consequently they are not considered to be a PRTI and are not considered further. Undivided Devonian rocks, however, are shown locally in the cores of anticlines to extend between 200 to 1000 m below surface and lie within the south-west England cleavage belt. They are therefore retained as HSR PRTIs.

The PRTIs are described in Table 3 in stratigraphical order from youngest to oldest (i.e. in downward succession), grouped by the three age ranges: younger sedimentary rocks, older sedimentary rocks and basement rocks. The descriptions include the distribution of the PRTI at surface (outcrop) and where the PRTI is present below the surface (subcrop) within the depth range of interest, along with key evidence for the interpretations. The main geological properties of the PRTIs and how these vary across the region are also summarised.

Brenchley and Rawson (2006) provides an excellent overview of the geology of the region, placing individual units in their regional and national context. The principal BGS report on the region, the Bristol and Gloucester Regional Guide (Green, 1992) also provides a useful overview. More detailed information is available in the memoirs accompanying the 1:50 000-scale geological maps. The stratigraphical framework reports for the Carboniferous of southern Great Britain (Waters et al., 2009), Mercia Mudstone Group (Howard et al., 2008), Early Jurassic (Cox et al., 1999) and Mid Jurassic (Barron et al., 2011) provide detailed summaries of the geological units. These reports may include terminology or nomenclature that has been updated since those publications were released. The term ‘mudstone’ follows BGS usage to include claystone and siltstone-grade siliciclastics (Hallsworth and Knox, 1999). The location of boreholes referred to in this chapter is shown on Figure 3.

The UK3D model (see glossary) was used as an information source for estimating the presence, thickness, depth of occurrence of geological units discussed below, and the geometry of their boundaries. Interpretations based on this model rely on borehole-derived geological relationships depicted in cross-sections, and it is possible that understanding of these relationships in some areas may be limited by cross-section data availability.

Maps showing the lateral distribution of PRTIs between 200 and 1000 m below surface, amalgamated into the generic host-rock types (i.e. EVAP, HSR and LSSR) are provided in Figures 6, 7 and 8 respectively. A further map showing the combined lateral extent of all PRTIs is provided in Figure 9.

Table 3 Schematic GVS for the Bristol and Gloucester 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 6, 7 and 8 for the regional distribution of PRTIs amalgamated by host rock model (i.e. LSSR, EVAP and HSR respectively).

	Geological period	Geological unit identified in NGS3D	Dominant rock type	Potential rock types of interest			Principal aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS	Cretaceous	Chalk Group	Chalk	N/A	N/A	N/A	Chalk Group (south-east only)
		Upper Greensand Formation (Selborne Group)	Sandstone and mudstone	N/A	N/A	N/A	Upper Greensand Formation (south-east only)
		Gault Formation (Selborne Group)		N/A	N/A	N/A	N/A
	Jurassic	Corallian Group	Limestone, sandstone, siltstone and mudstone	N/A	N/A	N/A	Corallian Group (south-east only)
		Kellaways and Oxford Clay formations (Ancholme Group)	Mudstone, siltstone, limestone and sandstone	N/A	Kellaways and Oxford Clay formations	N/A	N/A
		Great Oolite Group	Mudstone and limestone	N/A	Frome Clay Formation	N/A	Great Oolite Group limestones
		Inferior Oolite Group	Limestone, sandstone, mudstone and ironstone	N/A	N/A	N/A	Inferior Oolite Group limestones
		Lias Group	Mudstone, with sandstone, limestone and ironstone	N/A	Charmouth Mudstone, Whitby Mudstone, Dyrham and Blue Lias formations	N/A	Bridport Sand Formation (Upper Lias); Blue Lias Formation (marginal facies, Lower Lias)
	Triassic	Penarth Group (modelled with Mercia Mudstone Group)	Mudstone, limestone and sandstone	N/A	Westbury and Lilstock formations	N/A	N/A
		Mercia Mudstone Group	Mudstone with local siltstone, sandstone and evaporites	N/A	Blue Anchor, Branscombe Mudstone and Sidmouth Mudstone formations	Somerset Halite Member	Mercia Mudstone Group marginal facies
		Sherwood Sandstone Group	Sandstone with conglomerate and mudstone	N/A	N/A	N/A	Helsby Sandstone Formation
	Permian	Permian rocks (undivided)	Interbedded sandstone and conglomerate	N/A	N/A	N/A	Bridgnorth Sandstone Formation
OLDER SEDIMENTARY ROCKS	Carboniferous	Warwickshire Group	Sandstone and mudstone	N/A	Grovesend Formation	N/A	N/A
		South Wales Coal Measures Group	Mudstone, siltstone, sandstone and coal	N/A	N/A	N/A	N/A
		Marros Group	Sandstone, siltstone and mudstone	N/A	N/A	N/A	N/A
		Pembroke Limestone and Avon groups (Carboniferous Limestone Supergroup)*	Limestone and sandstone, volcanic extrusive rocks	N/A	N/A	N/A	Carboniferous Limestone Supergroup: Pembroke Limestone Group and Avon Group
	Devonian	Late Devonian rocks (undivided) = Upper Old Red Sandstone Group	Sandstone, conglomerate and mudstone	N/A	N/A	N/A	N/A
		Early Devonian rocks (undivided) = Lower Old Red Sandstone Group	Sandstone, conglomerate, siltstone and mudstone	N/A	N/A	N/A	N/A
		Devonian rocks (undivided)	Mudstone, siltstone and sandstone	Devonian rocks	N/A	N/A	N/A
BASEMENT ROCKS	Early Palaeozoic – ?Neoproterozoic	Unnamed mafic extrusive rocks, Silurian to Devonian	Andesite lava and tuff	Coalbrookdale Formation (andesite). 'Damery Beds' Tortworth	N/A	N/A	N/A
		Silurian rocks (undivided)	Mudstone, limestone	N/A	N/A	N/A	N/A
		Ordovician rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Cambrian rocks (undivided)	Mudstone, sandstone	N/A	N/A	N/A	N/A
		Proterozoic to Palaeozoic rocks (undivided)	Varied	N/A	N/A	N/A	N/A

*Modelled as 'Dinantian' (undivided) in NGS3D

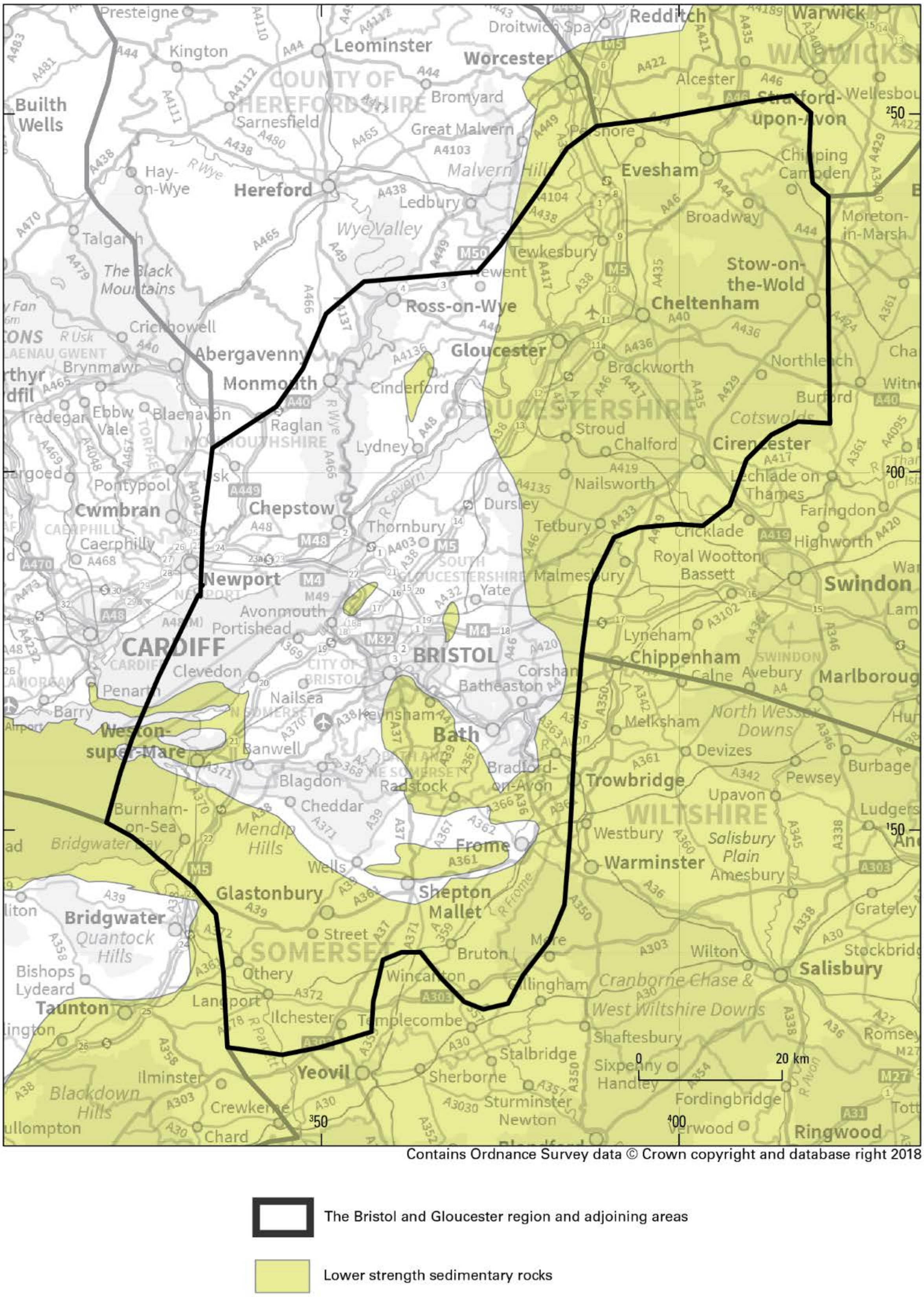


Figure 6 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Bristol and Gloucester region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data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

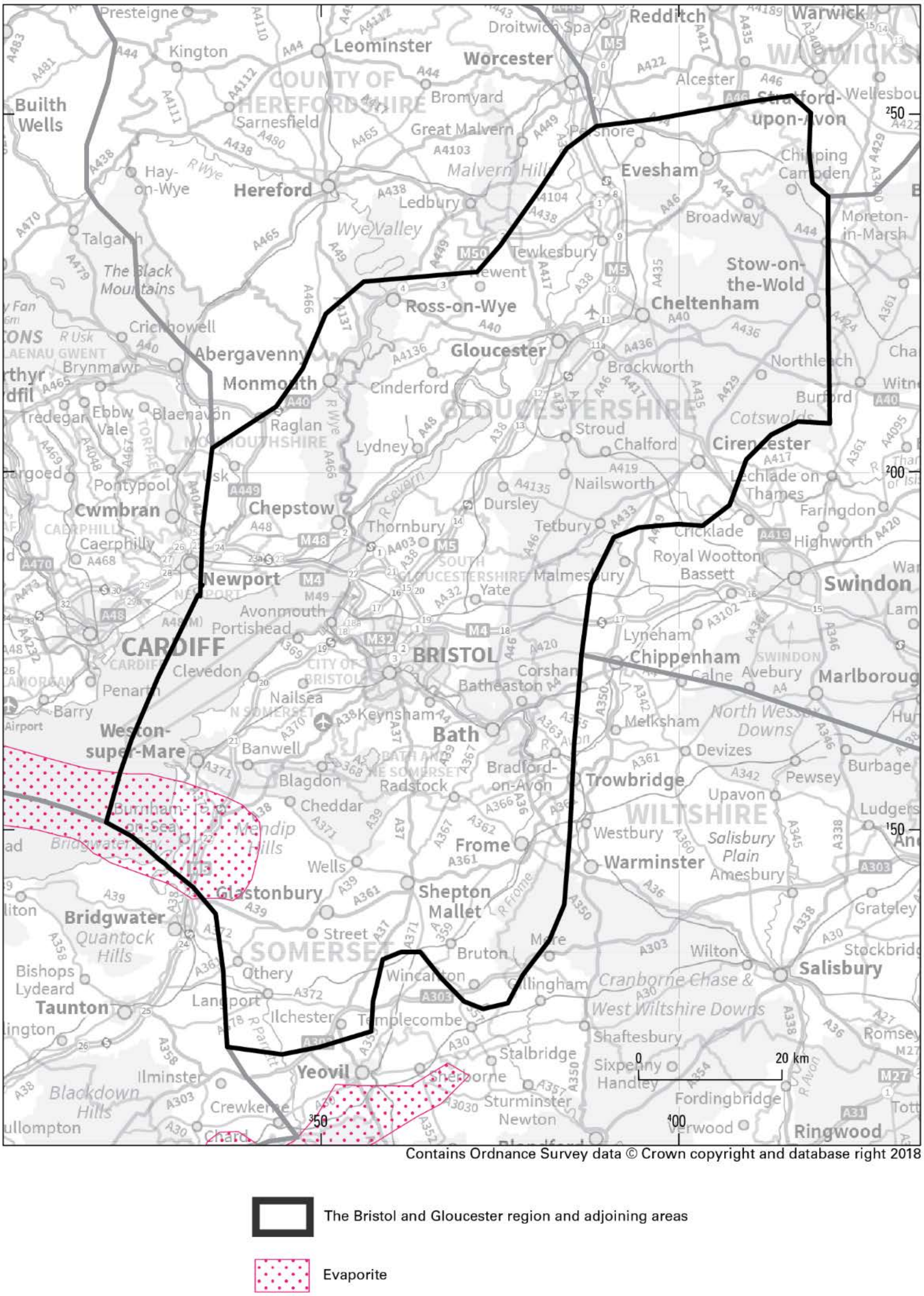


Figure 7 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the Bristol and Gloucester region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data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

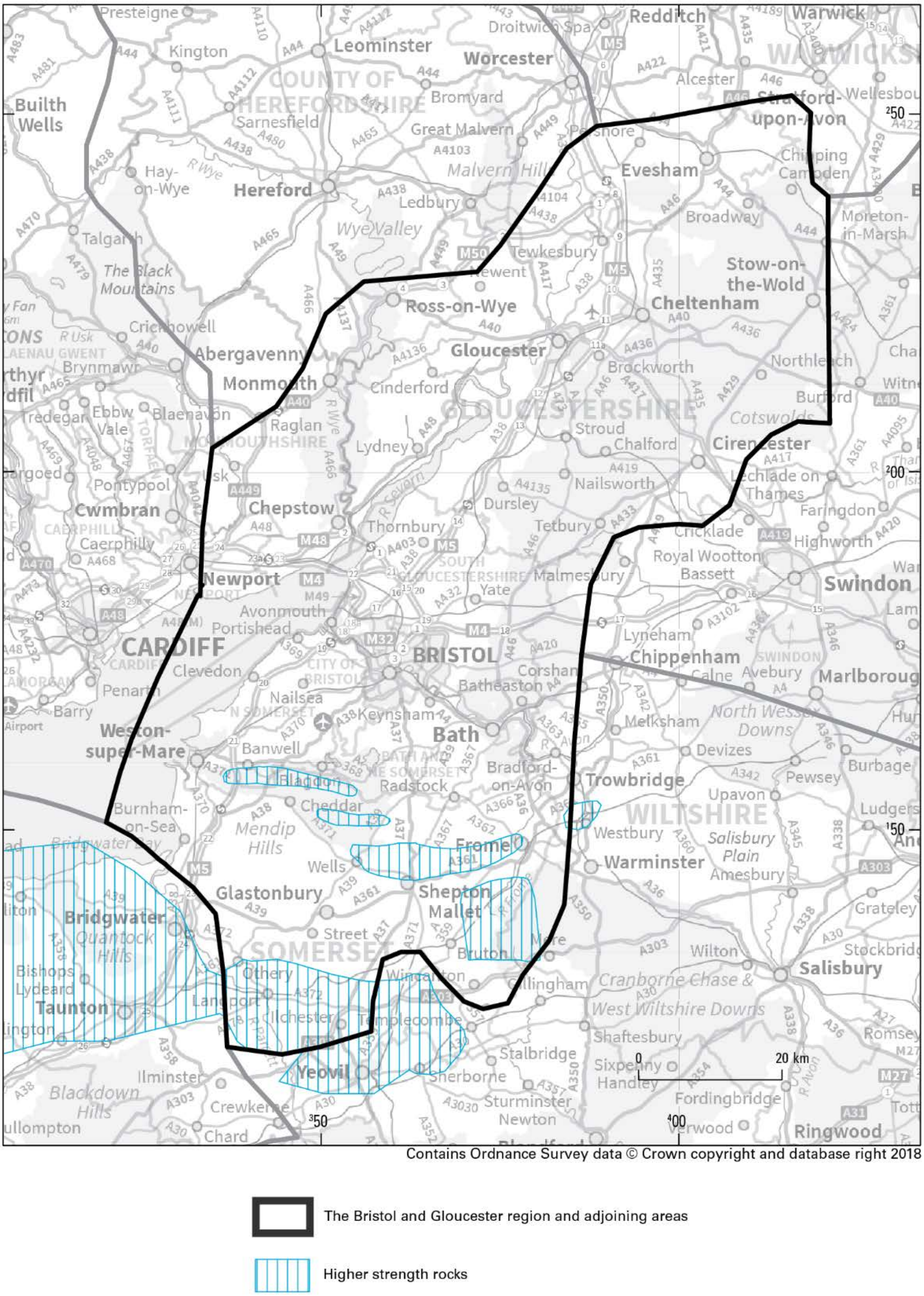


Figure 8 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Bristol and Gloucester region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data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

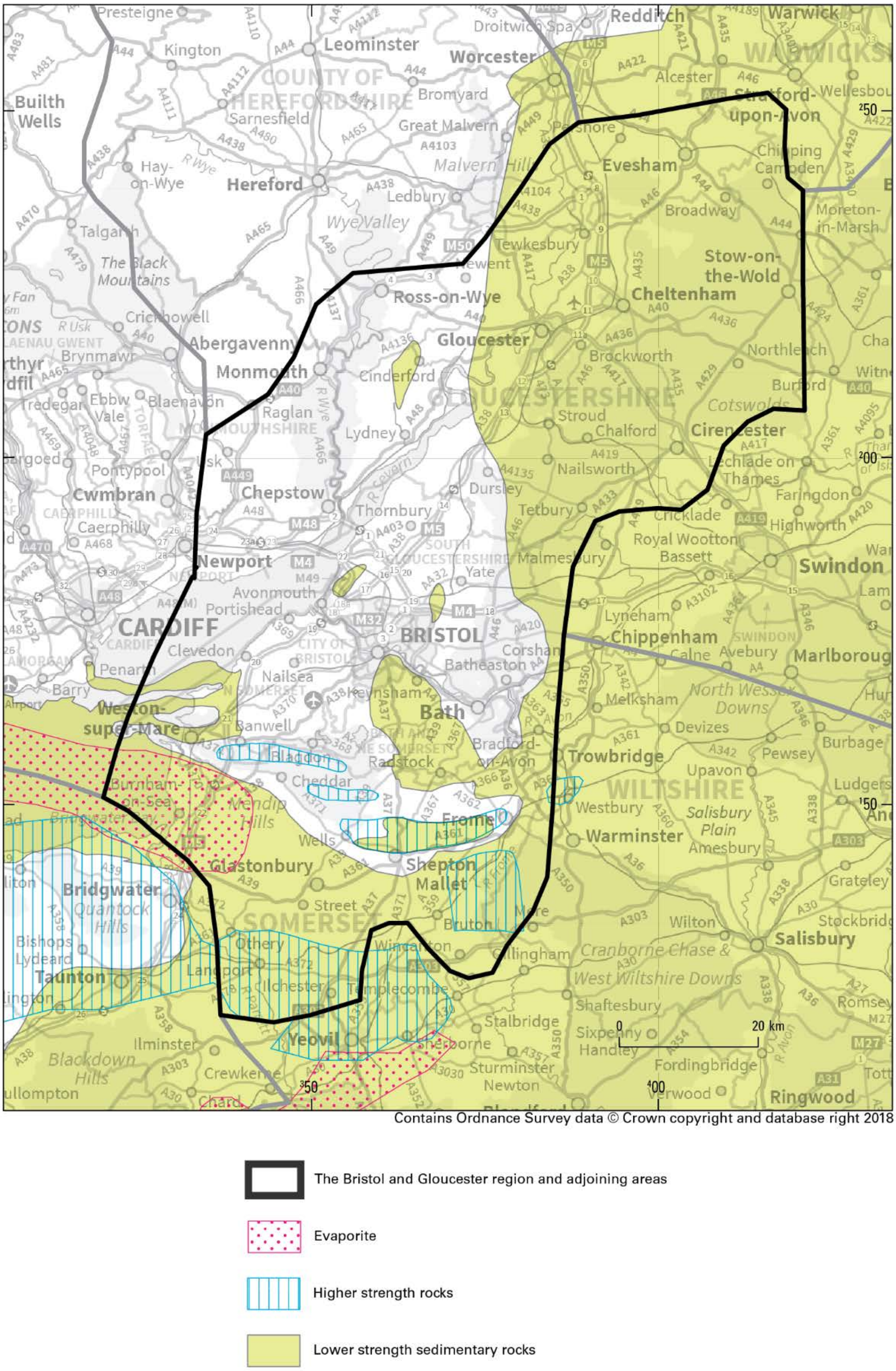


Figure 9 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Bristol and Gloucester region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological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

4.2.1 Younger sedimentary rocks

4.2.1.1 UNDIVIDED KELLAWAYS AND OXFORD CLAY FORMATIONS — LSSR

In the Bristol and Gloucester region, this PRTI comprises two mudstone-dominated rock units, the Kellaways Formation and the overlying Oxford Clay Formation. The units crop out in the south-east of the region, dipping at about 1–2º south-eastwards into the Wessex basin. Consequently they predominantly occur at depths less than 200 m and only descend into the depth range of interest (200m to 1000m below NGS datum) in the far south-east of the region (Figure 10) around Gillingham and Warminster, and here only the Kellaways Formation and lower part of the Oxford Clay Formation are likely to be within the depth range of interest. The unit is fully within the depth range of interest to the east of the region, in the Wessex basin.

These rocks are equivalent to the lower part of the Ancholme Group in the Midlands and Yorkshire. Though defined as individual formations, they are not always mapped as such and are often shown undivided. Although they attain an average thickness of over 150 m in the region (Figure 10), they form low-lying ground and are seldom exposed. They are underlain by the Great Oolite Group, a laterally variable sequence with significant changes in facies and thickness; it is in part a PRTI south of Bath (Frome Clay Formation). They are overlain by the Corallian Group (Figure 11) and locally the Gault Formation (a PRTI in other regions but not in the depth range of interest in the Bristol and Gloucester region) around Westbury.

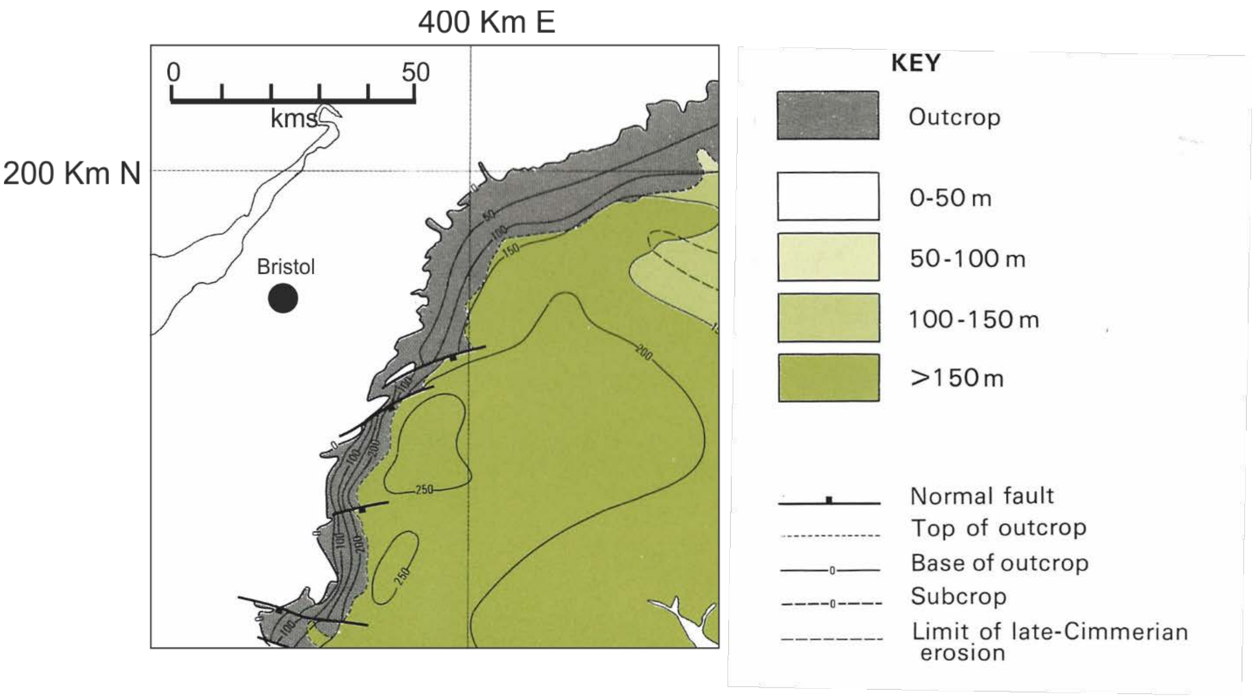


Figure 10 Isopachytes for the Kellways Formation, Oxford Clay Formation and part of the Corallian Group (from Whittaker, 1985). British Geological Survey © UKRI 2018

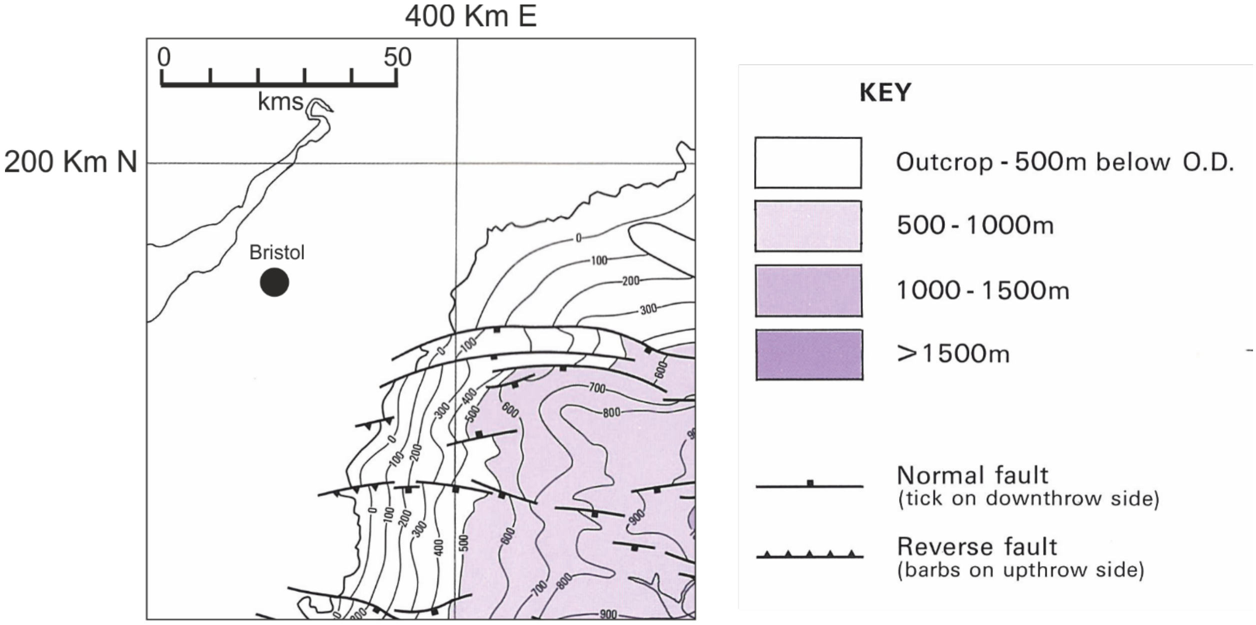


Figure 11 Depth to mid Corallian Group (metres below ordnance datum) (from Whittaker, 1985). British Geological Survey © UKRI 2018

Principal information sources

In the Bristol and Gloucester region the Kellaways and Oxford Clay formations have a very limited outcrop, occurring in a relatively narrow band of low-lying farmland between Chippenham, Trowbridge, Frome and the Blackmore Vale in Dorset, much of which is covered by thin superficial deposits. Information on the lithology of the formations is sourced mainly from a few deep-cored boreholes in the adjacent Hampshire region, for example Tytherington No. 2, Ashton 1 and Combe Throop (Figure 3), and old clay pits.

Rock type descriptions

The Oxford Clay Formation consists of grey mudstone, variably silty, with sporadic beds of secondary argillaceous, fine-grained limestone nodules. Across much of southern England it can be divided into three distinct members but they cannot be distinguished in this district from surface mapping. The upper part (Weymouth Member) is a pale grey, calcareous, smooth, blocky mudstone with silty limestone beds, especially near the top. The middle part (Stewartby Member) is a pale to medium grey, smooth to slightly silty, blocky mudstone, with subordinate beds of silty, shell debris-rich mudstone. The lower part (Peterborough Member) is a brownish-grey, fissile, organic-rich ('bituminous') silicate mudstone with subordinate beds of pale to medium grey, blocky mudstone. It reaches a maximum thickness in south Dorset of 185 m and is 146 m thick in the Urchfont Borehole (Figure 3) near Devizes, in the adjacent Hampshire region.

The Kellaways Formation consists of grey, commonly silty or sandy mudstone with beds of generally calcareous siltstone and sandstone, mostly within the upper part. The formation is typically 21 to 25 m thick, reaching a maximum thickness of 50 m in south Dorset. North of Chippenham it is divisible into two members, the Kellaways Sand Member (formerly called the Kellaways Rock) and the underlying Kellaways Clay Member, but these cannot be distinguished in the south. These sand beds are conspicuously well cemented with calcium carbonate. The base of the Kellaways Sand Member is taken at the base of the lowest substantial sandstone/siltstone unit resting on the predominantly mudstone succession of the underlying Kellaways Clay Member.

4.2.1.2 GREAT OOLITE GROUP — LSSR

The Great Oolite Group is a lithologically diverse and laterally variable group of Mid Jurassic rocks, predominantly consisting of shallow marine oolitic limestones (including the famous Bath Stone), but which also which includes some mudstone units, of which one, the Frome Clay Formation, constitutes a PRTI. In the Bristol and Gloucester region, the Great Oolite Group underlies much of the Cotswolds and extends south in a narrower outcrop to the Dorset coast. A significant lithological change occurs near Wellow, between Bath and the Mendip Hills. Here the shallow marine Chalfield Oolite Formation passes laterally southwards into a predominantly mudstone sequence, the Frome Clay Formation, a PRTI. This formation is generally 20 to 50 m thick in Wiltshire and Somerset, and continues south to the coast where it is up to 70 m thick. It crops out in a narrow zone between Frome and the Dorset coast, generally dipping gently east. In the subcrop, the facies change between the mudstone-dominated Frome Clay and the oolitic limestones extends south-east from Bath towards Southampton, thus limiting the eastward subcrop of the Frome Clay Formation to within 30 to 40 km of the present outcrop. Figure 12 shows the depth to the top of the Great Oolite Group. This indicates that the zone in which the Frome Clay Formation is present at the depth range of interest is east of a line between Frome and Sturminster Newton.

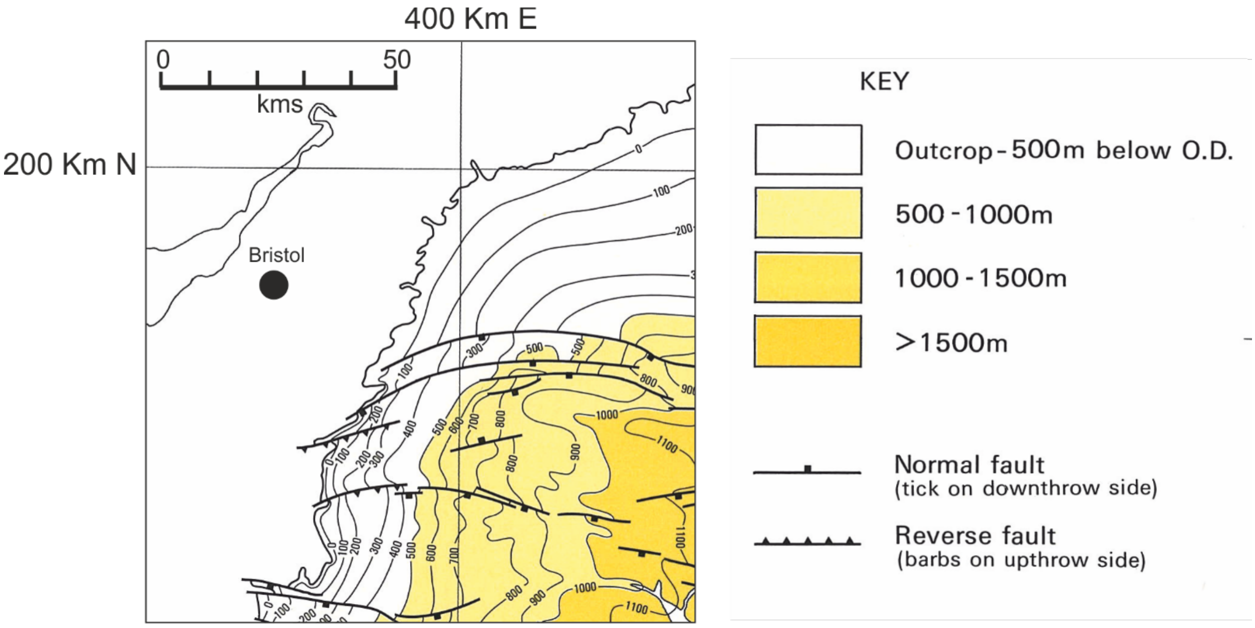


Figure 12 Depth to top of Great Oolite Group (after Whittaker, 1985). British Geological Survey © UKRI 2018

Principal information sources

In the Bristol and Gloucester region, the limestone units that make up the Great Oolite Group are well known from numerous outcrops, quarries and mines, and are generally well mapped. However, the mudstone facies south of Bath is less well exposed, as it underlies generally low or gently sloping ground at the base of a minor escarpment, although the extent is commonly well defined. The transition between the oolite facies around Bath is known from sections and boreholes (Penn and Wyatt, 1979) and identified in the subcrop from boreholes and seismic data. Isopachyte maps (Figures 13 and 14) show the extent and maximum thickness of the Frome Clay Formation (Selwood, 1989; Bristow et al., 1999). The most northerly, fully argillaceous occurrence of the Frome Clay Formation is in the Frome (Gibbet Hill) Borehole (Figure 3) (Penn and Wyatt, 1979). Further south, in the Bratton Seymour Borehole, the Frome Clay Formation is 48.7 m thick, reaching a maximum thickness of about 70 m near Wincanton (Bristow and Donovan, 1999). It is also present in the Purse Caundle Borehole (Figure 3) and the Winterborne Kingston Borehole (see Figure 3 in corresponding Hampshire and adjacent areas region companion report) in the adjacent Hampshire region (Penn, 1982).

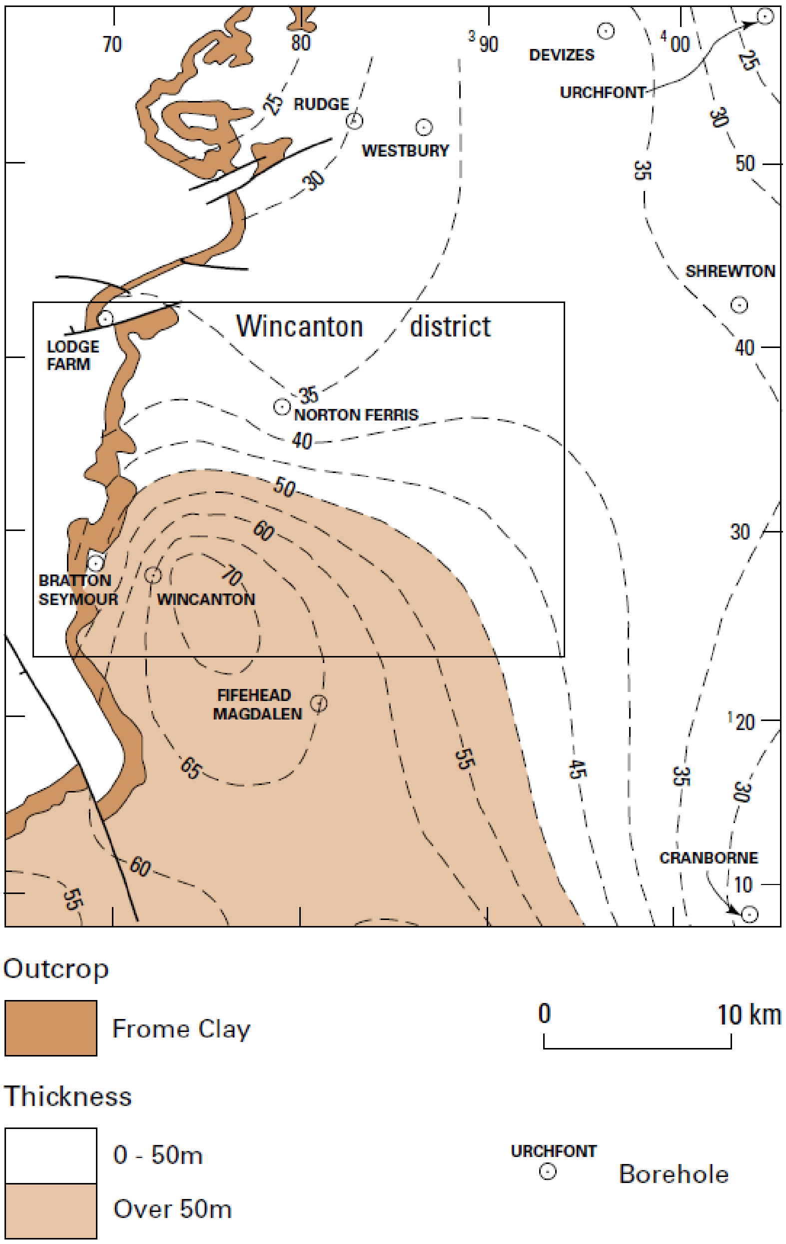


Figure 13 Isopachyte map of the Frome Clay Formation (contours at 5 m intervals); from Bristow et al. 1999. British Geological Survey © UKRI 2018

Rock type descriptions

The Frome Clay Formation comprises between 20 and 70 m of blue-grey and olive-grey, calcareous, silty to fine-grained sandy mudstones interbedded with darker olive-grey, less silty, bituminous mudstone and minor, generally fine-grained limestone units. A 5 m-thick unit of fossiliferous, nodular, argillaceous, shelly, bioturbated limestone interbedded with thick mudstone beds is developed at the base (Wattonensis Bed Member). This is poorly developed around Frome, but thickens south to the Dorset coast and offshore. A couple of minor, oyster-rich limestone beds occur higher up in the sequence.

The transition between the oolitic limestone facies around Bath and the Frome Clay Formation is demonstrated in the Baggridge No. 2 Borehole (Figure 3), which proves variably calcareous mudstone with minor limestone beds; the Wattonensis Bed Member is not developed at base here. To the north, within 1 to 3 km, the formation passes laterally into the limestone beds of the Chalfield Oolite Formation and the calcareous nature of some of the beds in the borehole shows this lithological change (Penn and Wyatt, 1979).

The Frome (Gibbet Hill) Borehole (Figure 3) penetrates the full thickness of the formation, comprising variably calcareous mudstone with minor limestone beds. The Bratton Seymour Borehole (Figure 3) proves the lower part of the formation, comprising around 4 m of interbedded limestone and mudstone of the Wattonensis Limestone Member at the basal section overlain by 45 m of olive-grey, calcareous mudstone, variably bioclastic with a fauna dominated by bivalves (Barton et al., 1993). Further south, in the adjacent Hampshire region, the Winterborne Kingston Borehole (SY89NW1) penetrates 4.4 m of interbedded limestone and mudstone (Wattonensis Limestone Member) at the base, overlain by 5.4 m of dark grey fissile mudstone and by 50.5 m of grey calcareous mudstone (Penn, 1982).

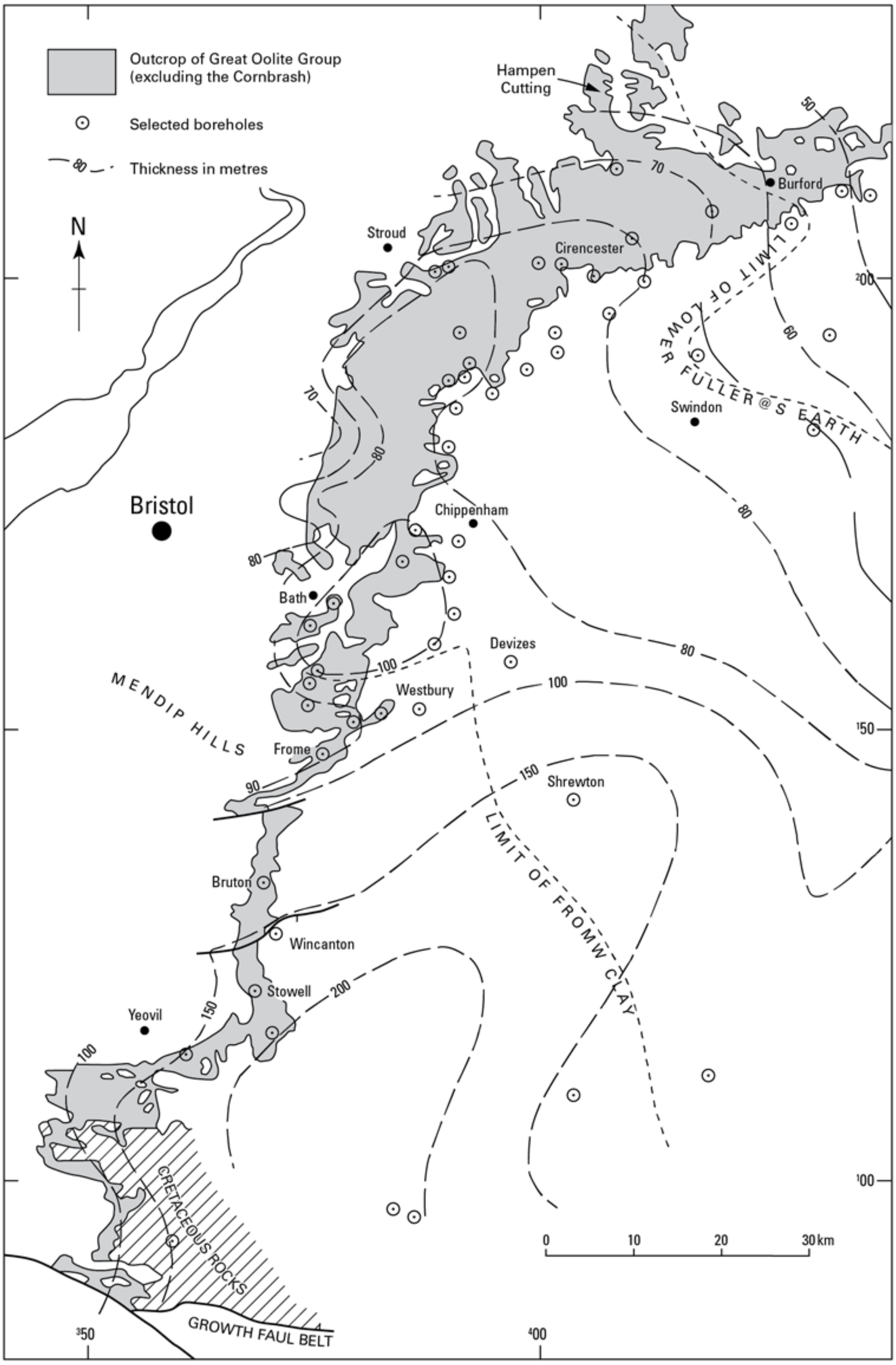


Figure 14 Isopachyte map of the Great Oolite Group, showing the north-eastern limits of the Frome Clay Formation (adapted from Green, 1992). British Geological Survey © UKRI 2018

4.2.1.3 Lias Group — LSSR

The Lias Group is a mudstone-dominated succession containing significant amounts of silty mudstone and limestone, the latter typically occurring as thin units interbedded with mudstone (Figure 15). The upper part of the Lias Group is generally sandier and with thicker limestone units. Regionally, the Lias Group consists of an upper unit of mudstone (Whitby Mudstone Formation), a middle unit dominated by sandstone and ferruginous limestone with some mudstone (Dyrham and Marlstone Rock formations; up to 35 m thick) and a lower unit of mudstone (Charmouth Mudstone Formation), underlain by more mudstone with persistent limestone beds (Blue Lias Formation) The Whitby Mudstone Formation is present only in parts of the Worcester basin (Figure 5); further south it is replaced by the Beacon Limestone and Bridport Sands formations (Cox et al., 1999).

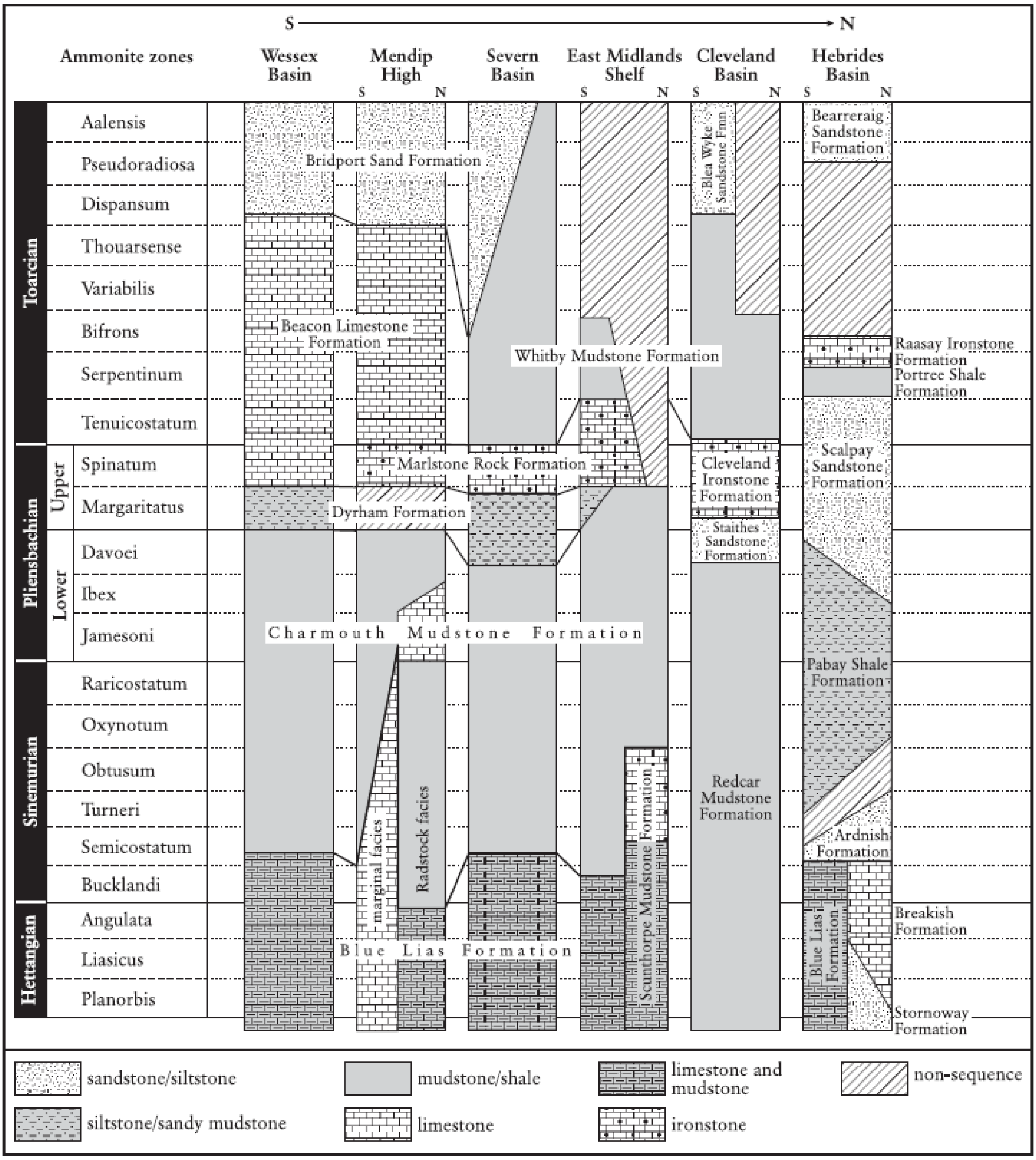


Figure 15 Lithostratigraphy for the Lias Group across the UK, based on Cox et al., 1999 (from Simms et al., 2004). British Geological Survey © UKRI 2018.

The deposition of the Early Jurassic in the Bristol and Gloucester region was influenced by the development of several major sedimentary basins, each of which accumulated hundreds of metres of sediment as part of a total Mesozoic fill that in some places is several kilometres thick. To a large extent the configuration of these various Mesozoic basins was determined by pre-existing faults. Several distinct Early Jurassic depositional areas can be recognised in Britain, of which four occur in the Bristol and Gloucester region. These are the Wessex basin; the Bristol Channel (Somerset) basin; the Mendip high and Bristol–Radstock shelf, and the Worcester (Severn) basin (Figure 5).

Within these basins, there are significant changes in sediment facies and thickness across the region (Figures 16 and 17). In the north of the region, borehole and geophysical data demonstrate a dramatic south-eastward thinning of the Lias Group from over 500 m in the deepest part of the Worcester basin (Figure 5) to less than 200 m in the south-east, where it rests on the London platform. This thinning results from the loss of the basal beds by overlapping strata, and the remainder of the succession is condensed (Sumbler et al., 2000). The central axis of the Worcester basin extends south from Bredon Hill towards Cheltenham and Swindon where around 400 to 500 m of sediment is preserved. The Lias Group also thins to the south and west, thinning to around 120 to 135 m around Bristol and Bath (Figure 16). It then thins dramatically onto the Bristol–Radstock shelf and over the Mendip high, where it is present in marginal littoral facies comprising conglomeratic limestones, or it is absent. South of the Mendip Hills, the Lias Group thickens into the centre of the Bristol Channel–Somerset basin, where up to 234 m of mudstone has been proved. The Lias Group also thickens to the south-east into the Wessex basin with over 400 m preserved around Shrewton, and 600 m south-east of Yeovil.

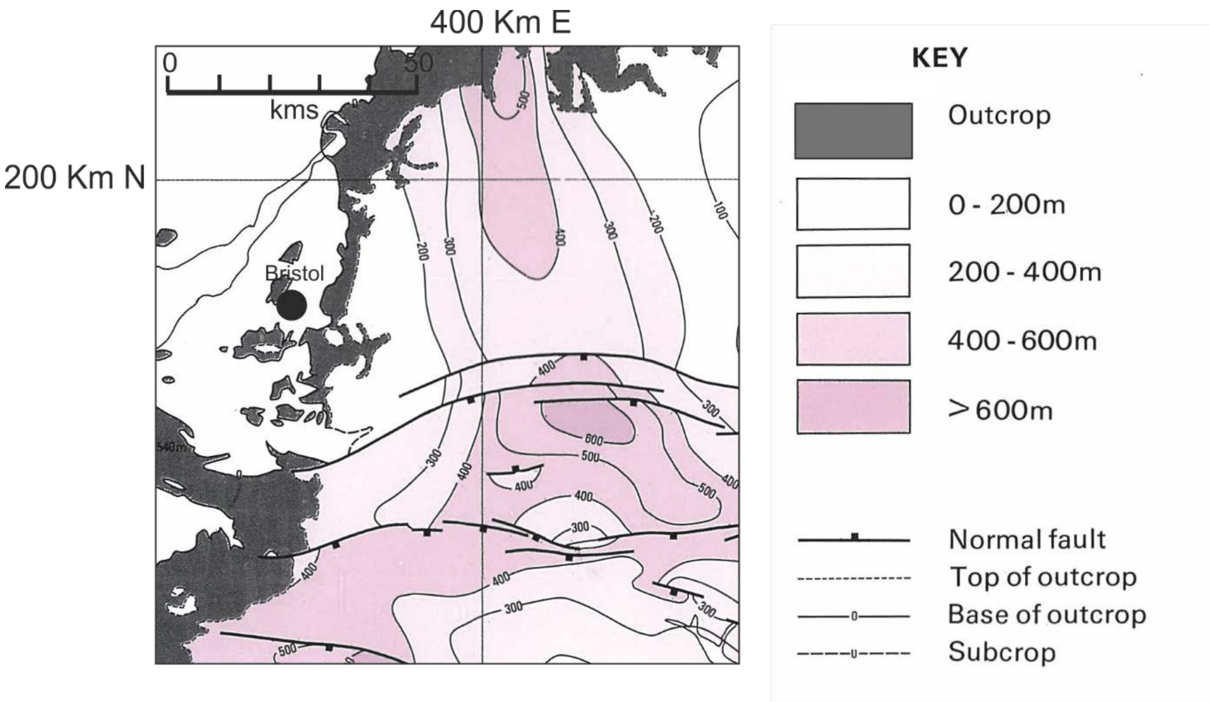


Figure 16 Isopachytes for the Lias Group (black represents outcrop). From Whittaker, 1985. British Geological Survey © UKRI 2018

Throughout much of the area, the Lias Group generally dips gently to the east or south-east, descending to depths approaching 1 km in the Salisbury–Andover area (Figure 18). Thus areas where the Lias Group occurs in the depth range of interest are largely restricted to the south-east of the region, in a north–south zone from Swindon through Chippenham and Warminster to Yeovil. The geological structure is more complex around Bristol and over the Mendip Hills, although here the Lias Group does not extend to depths in excess of 200 m. Further south, in the centre of the Bristol Channel–Somerset basin, the base of the Lias Group descends to around 400 m depth around Brent Knoll (Figure 19).

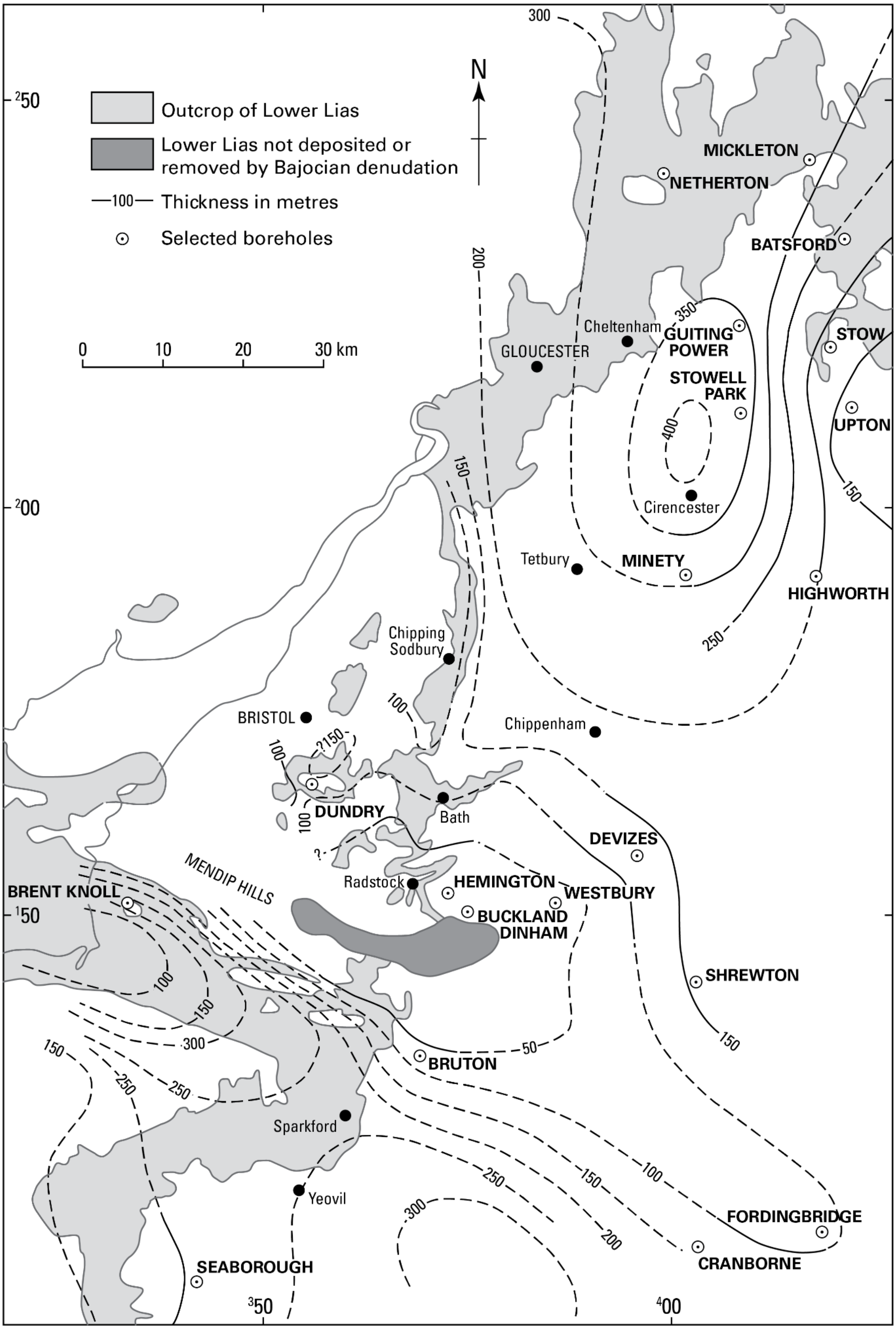


Figure 17 Thickness variations in the lower Lias Group (adapted from Green, 1992). British Geological Survey © UKRI 2018

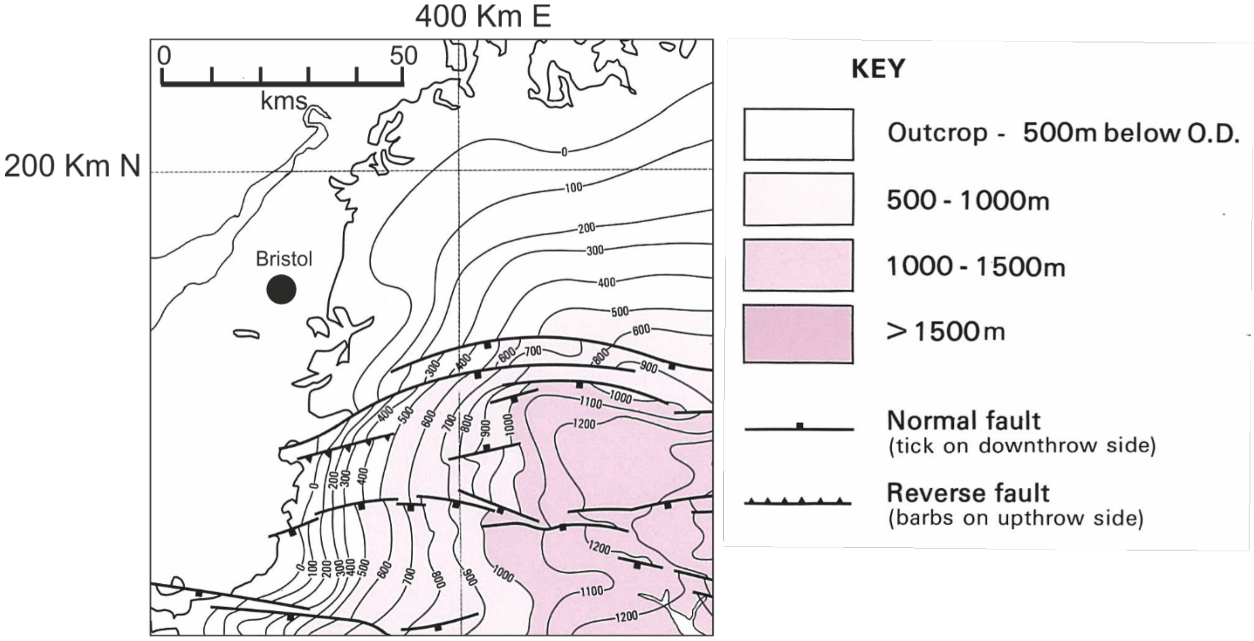


Figure 18 Depth to the top of the Lias Group, metres below ordnance datum. From Whittaker, 1985. British Geological Survey © UKRI 2018

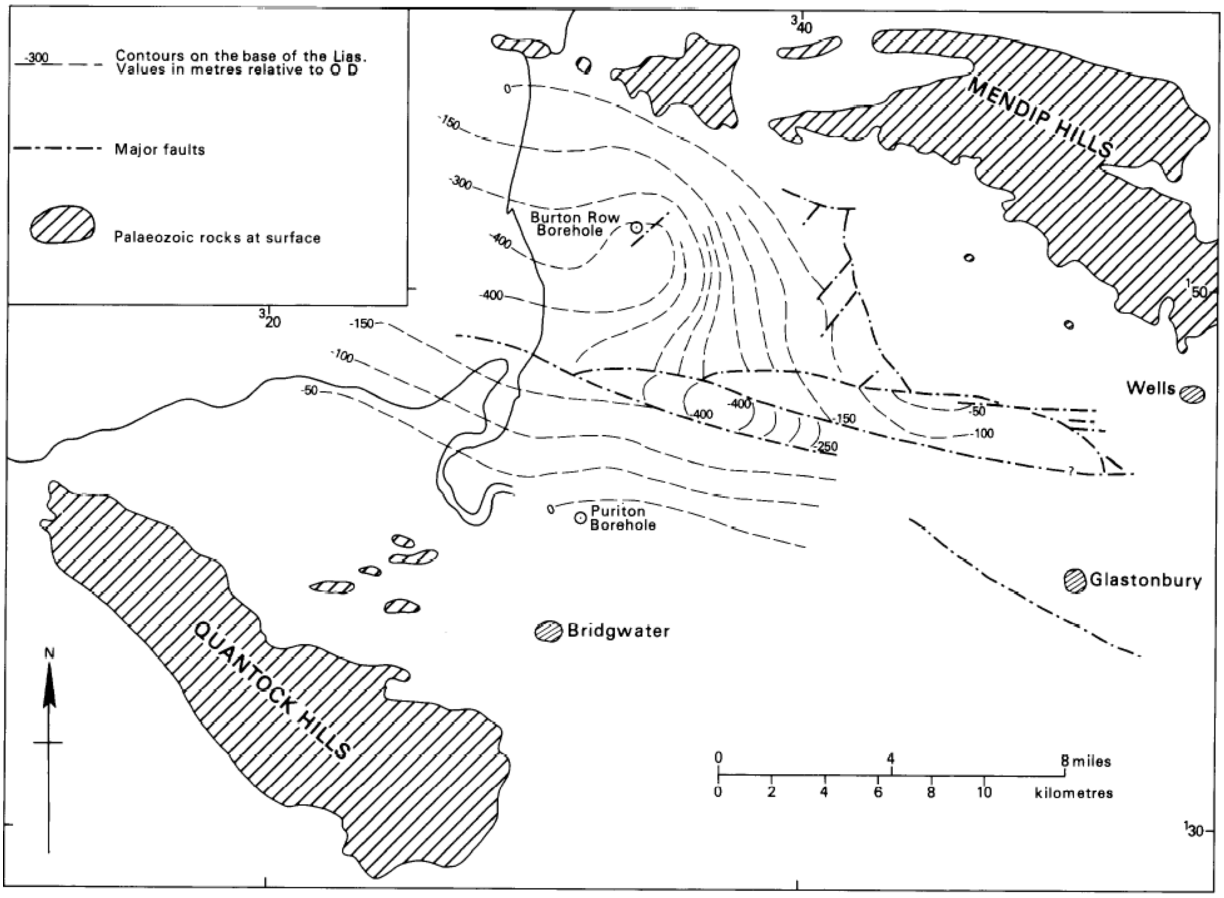


Figure 19 Structure contours on the base of the Lias Group in the Bristol Channel–Somerset basin (Whittaker and Green, 1983). British Geological Survey © UKRI 2018

Principal information sources

The Lias Group is generally well mapped throughout much of its surface outcrop, although there are relatively few good exposures of the mudstones units as they typically form low-lying ground. The Blue Lias Formation is well exposed on the north Somerset coast between Watchet and Hinckley Point. The mudstones used to be exposed in old brick pits but few now remain. Over much of the region, the Lias Group occurs at or near the surface. In these areas it is well documented, partly due to the well-constrained ammonite faunas. It is only in the east of the region where the rocks become more deeply buried. In these areas, they are known mostly from deep boreholes and from seismic data. Key boreholes, shown on Figure 3, include Guiting Power, BGS Bredon Hill No. 1 (Lalu Barn), BGS Stowell Park, BGS Elton Farm, BGS Burton Row, BGS Twyning, Bruton, BGS Upton, Yarnbury 1 and Westbury Station boreholes.

Details of the Lias Group are documented in the Bristol and Gloucester Regional Guide (Green, 1992), various geological sheet memoirs, the Lower Jurassic Stratigraphic Framework Report (Cox et al., 1999) and the Geological Conservation Review on the British Lower Jurassic Stratigraphy (Simms et al., 2004).

The Dyrham Formation is dominated by grey to greenish-grey, silty to sandy mudstone. There may be local developments of ferruginous limestone or sandstone beds, and nodules of diagenetic carbonate or siderite. Sporadic large concretions occur within the sandstones. It is generally very poorly exposed. Like the Charmouth Mudstone Formation, there are significant thickness variations across the various basins in the Bristol and Gloucester region. In the Worcester basin, the formation is thickest in the mid-Cotswolds, where it is up to 75 m thick. In the BGS Stowell Park Borehole, the Dyrham Formation is 54 m thick, thinning to 35 m in the BGS Bredon Hill No. 1 (Lalu Barn) Borehole; it is 20 m thick around Dyrham and less than 10 m south of Bristol. In Somerset the Dyrham Formation thickens again into the Bristol Channel basin, with 86 m being recorded near Bruton.

The Charmouth Mudstone Formation consists of dark to pale grey mudstone, laminated at some levels, locally with phosphatic or sideritic concretions and tabular beds of argillaceous limestone. On the coast in Dorset, several discrete members can be identified, some of which are locally mapped but in general inland these units are not easily recognisable. In the Worcester basin, the Charmouth Mudstone Formation reaches its maximum thickness of around 290 m to the north and east of Cheltenham with some 268 m proved in the Guiting Power Borehole. It thins to the east, and is only about 130 m thick in the north-east of the district. Nodules and thin beds of argillaceous limestone are developed at some levels, particularly near the top of the formation. Further south in the BGS Elton Farm Borehole, it is 123.8 m thick, thinning over the Mendip high (Figure 5) before thickening again into the Bristol Channel basin where 122 m of mudstone is preserved.

The lowest part of the Lias Group is the Blue Lias Formation. This consists of cyclic, decimetre-scale alternations of argillaceous limestone and mudstone. Individual limestones are typically 0.10 to 0.30 m thick, and intervening mudstones, which may contain limestone nodules, are typically less than 1 m thick. The upper boundary coincides with a marked upward decrease in abundance of limestone beds, sometimes associated with a marked decrease in their individual thickness and lateral persistence. In the Worcester basin, the formation thins from about 75 m in thickness in the north-west, to about 10 m in the south-east. It is 64 m thick in the Guiting Power Borehole. It thins further south over the Mendip high, where it is often in a littoral facies or absent, before thickening markedly into the Bristol Channel basin. It is around 175 m thick on the north Somerset coast.

4.2.1.4 PENARTH GROUP — LSSR

The Penarth Group is modelled undivided from the Mercia Mudstone Group in NGS3D. The Late Triassic Penarth Group (previously known as the Rhaetic Beds) was deposited in a shallow marine setting subject to episodic lagoonal and estuarinal conditions, during a marine transgression (Barton et al., 2002). The Penarth Group is present in the southern part of the region, primarily south of the Bristol Channel; it is at the surface in areas around Bristol city but only attains the depth range of interest in the south-eastern parts of the region (Figure 20).

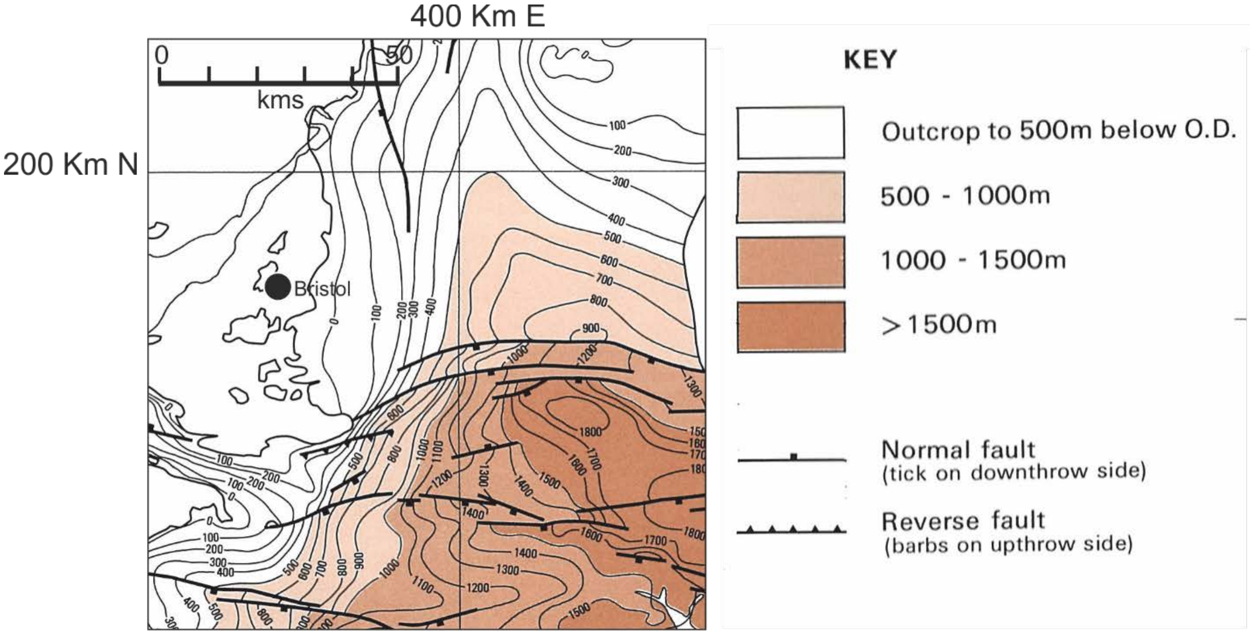


Figure 20 Depth to top of Penarth Group/Mercia Mudstone Group (metres below ordnance datum) (from Whittaker, 1985). Note that the top of the Penarth Group is no more than 20 m above the top of the Mercia Mudstone Group. British Geological Survey © UKRI 2018

Principal information sources

The Penarth Group is well mapped throughout its surface outcrop and is readily identifiable and differentiated from the stratigraphically adjacent formations. The Westbury Formation generally forms lower-lying ground in the region and is less well exposed at the surface, owing to its high mudstone component. By contrast the more competent Lilstock Formation can form notable escarpments in the region e.g. the Windmill Hill (Bristol), Cotham (Bristol) and Totterdown (south of Avon). Key boreholes include the Bruton 1, Hemington and Radstock (Borehole ST75SW_1) boreholes.

Rock type descriptions

The Penarth Group in the region is composed of two formations: the older Westbury Formation and younger Lilstock Formation.

The Lilstock Formation is subdivided in the region into two members: the stratigraphically older Cotham Member and younger Langport Member. The Langport Member has a proven thickness in Bruton 1 Borehole of about 7 m and is characterised by limestones with interleaving calcareous mudstones. Traces of pyrite and broken shelly fauna can be common throughout the unit. The Cotham Member has a proven thickness in the same boreholes of just over 1.5 m with the boundary with the overlying Langport Member taken at the base of the last of the limestone beds. The Cotham Member is comprised of grey to grey-green, calcareous, laminated mudstones. Subordinate beds of oolitic sandstone and siltstone may present, alongside traces of pyrite.

The Westbury Formation is the lowermost formation in the Penarth Group and has a proven thickness of about 2 m in the Bruton 1 Borehole, although other boreholes in the region prove thicknesses up to around 7 m (Hemington Borehole). The Westbury Formation is comprised of dark grey to black, finely laminated mudstones (shales); locally these mudstones maybe finely micaceous and/or contain phosphatised quartz pebbles at their base. Gastropods and fish remains can be common in the more muddy parts of the formation.

4.2.1.5 Mercia Mudstone Group (incorporating the Blue Anchor, Branscombe Mudstone and Sidmouth Mudstone formations (LSSR PRTIs) and the Somerset Halite Member (EVAP PRTI)

The Triassic Mercia Mudstone Group was deposited in a continental, terrestrial setting with considerable local relief, under arid or semi-arid conditions. The terrestrial setting comprises a complex depositional environment with uplands shedding sediment via fluvial systems into lowland evaporitic basins. The Mercia Mudstone Group is composed mainly of red and, less commonly, green and grey mudstone and siltstone, with some localised sandstone units and breccias; the latter are concentrated around the flanks of Palaeozoic highs. Substantial deposits of halite occur in the thicker, basinal successions in central Somerset, and have been included as a PRTI (as the Somerset Halite Member). Sulphate deposits (gypsum and anhydrite) and sandstone beds are common at some stratigraphical levels but are a minor constituent throughout most of the group. The group has been divided into several distinct formations, mostly mudstones but with some sandstone units and marginal breccias (Figure 21). These are, in descending order, the Blue Anchor, Branscombe Mudstone, Arden Sandstone and Sidmouth Mudstone formations; all, with the exception of the Arden Sandstone Formation, are PRTIs.

Like the Lias Group, the Triassic Mercia Mudstone Group of the Bristol and Gloucester region was deposited in a complex set of fault-controlled basins and sub-basins, which continued into the Early to Mid Jurassic, with areas of intervening high ground. The disposition of these basins and the existing topography influenced sediment thickness and facies within the group (Figure 22). The greatest thicknesses occur in the centre of the basins where 450 to 550 m of sediment may be preserved. In the north of the region, significant thicknesses of sediment were deposited in the Worcester basin (Figure 5), which forms a complex half-graben structure. The thickest deposits occur in the west of the basin, close to the Eastern Boundary Fault of the Malvern Hills.

Around Bristol and the Mendip Hills, the deposition of the Mercia Mudstone Group was strongly influenced by the existing topography. Complex breccias (Mercia Mudstone marginal facies or 'dolomitic conglomerate') developed as alluvial fans or screes around significant Palaeozoic uplands, extending out into the surrounding basins. These uplands included the Mendip Hills, Broadfield Down and the Carboniferous Limestone Supergroup ridges between Clevedon, Portishead and Bristol. Mudstone deposits several hundred metres thick accumulated in the low lying ground between these upland areas (Figure 22), locally interspersed with thin sandstones or 'skerries' in places, such as the Redcliffe Sandstone Member and the Arden Sandstone Formation.

In the south of the region, the basins have an overall east–west trend, reflecting formation by extensional reactivation of Variscan compressional structures (Chadwick, 1986). The Wessex–Bristol Channel basin system comprises a number of sub-basins, including the Wardour and Pewsey sub-basins in the east of the region. Thick deposits of mudstones with evaporites accumulated in the centre of the Bristol Channel basin.

The Mercia Mudstone Group crops out across east Devon, Somerset and across the Bristol region (Figure 20) and extends northwards through the Severn valley past Gloucester towards Worcester. It typically forms low-lying ground, underlying much of the alluvial flats alongside the Severn estuary. In the south-east of the region the Mercia Mudstone Group dips eastwards below younger Mesozoic rocks into the Wessex basin, reaching depths in excess of 1 km. Thus areas where the top of the Mercia Mudstone Group exceeds 200 m depth occur in the south-east of the region around the margins of the Wessex basin in a north–south zone from Yeovil through Warminster, Chippenham to Swindon, but also extending north in a broad zone along the axis of the Worcester basin towards Cheltenham, and west along the core of the Bristol Channel basin into Bridgewater Bay. Across much of the Bristol–Bath area, the Mercia Mudstone Group does not extend down into the depth range of interest, except in a few areas (Figure 23).

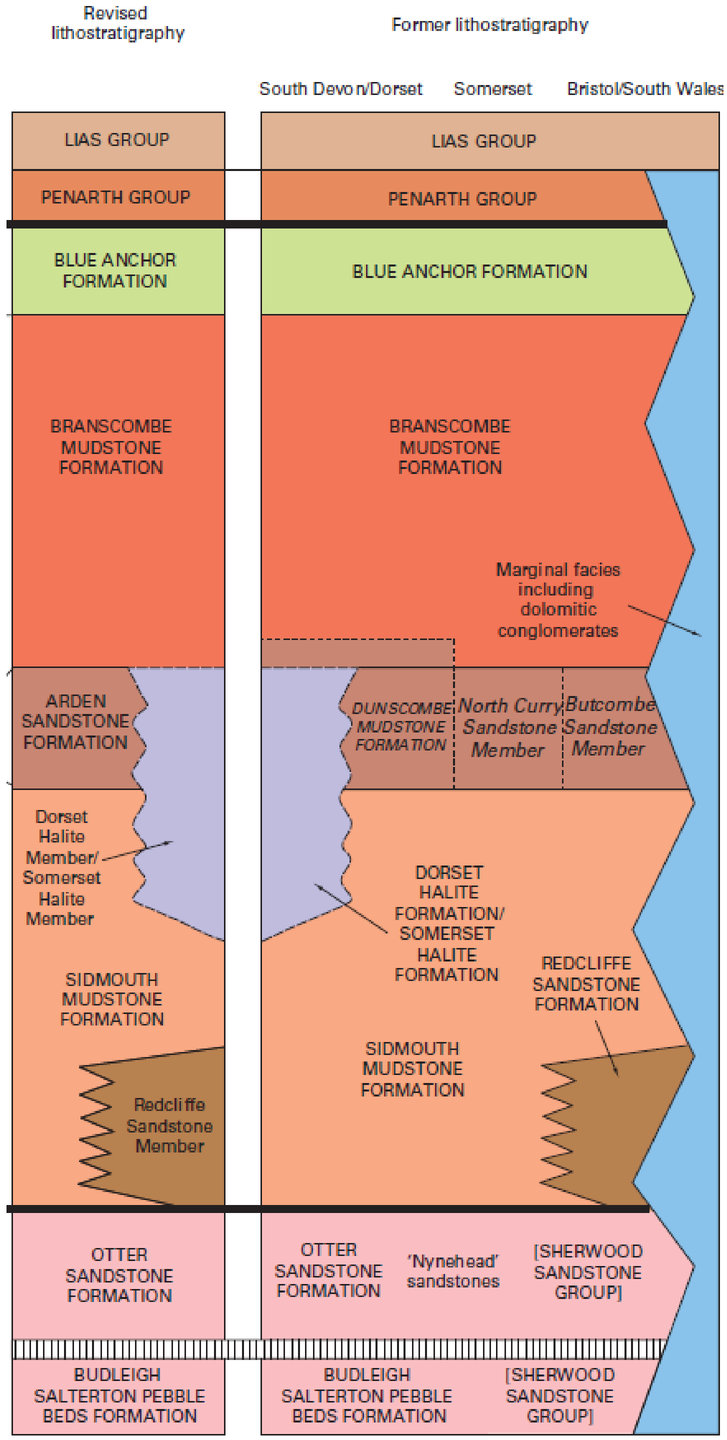


Figure 21 Stratigraphical nomenclature of the Mercia Mudstone Group (delineated by the thick black lines) comprising the Sidmouth Mudstone, Arden Sandstone, Branscombe Mudstone and Blue Anchor formations (from Howard et al., 2008). British Geological Survey © UKRI 2018

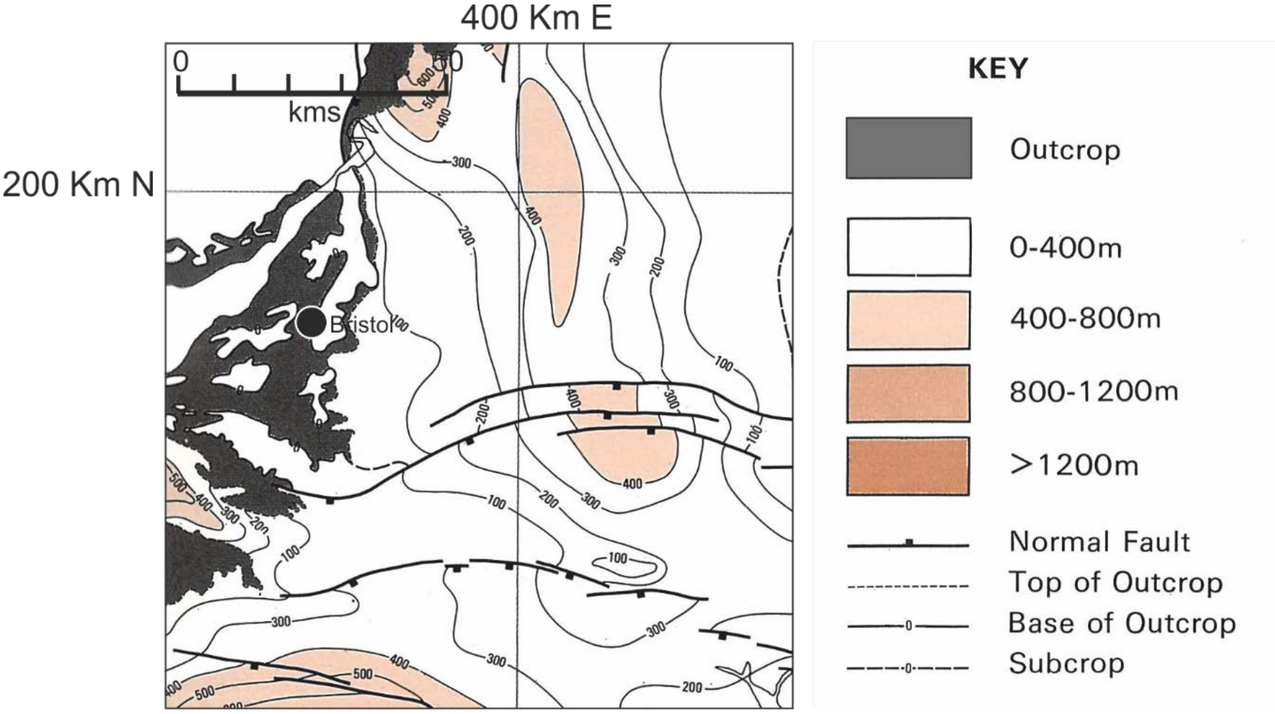


Figure 22 Isopachytes for the Mercia Mudstone and Penarth groups (from Whittaker, 1985). British Geological Survey © UKRI 2018

Principal information sources

Although it often forms low-lying ground, the Mercia Mudstone Group is locally well exposed in the Bristol and Gloucester region, with good outcrops occurring at Aust Cliff and on the north Somerset coast at Blue Anchor. It gives rise to characteristic red soils that are easily mapped. However, it is often concealed beneath younger, superficial deposits.

The lithological classification of the Mercia Mudstone Group is discussed by several authors including Warrington et al. (1980); Gallois (2001); Howard et al. (2008); Green (1992), and Benton et al. (2002). Local details are provided in the 1:50 000 map sheet geological memoirs. Within the basin, thickness and facies are known mostly from deep boreholes, and from seismic data. Key boreholes, shown in Figure 3, include the BGS Burton Row, BGS Twyning, Eldersfield, Worcester Heat Flow and Puriton boreholes.

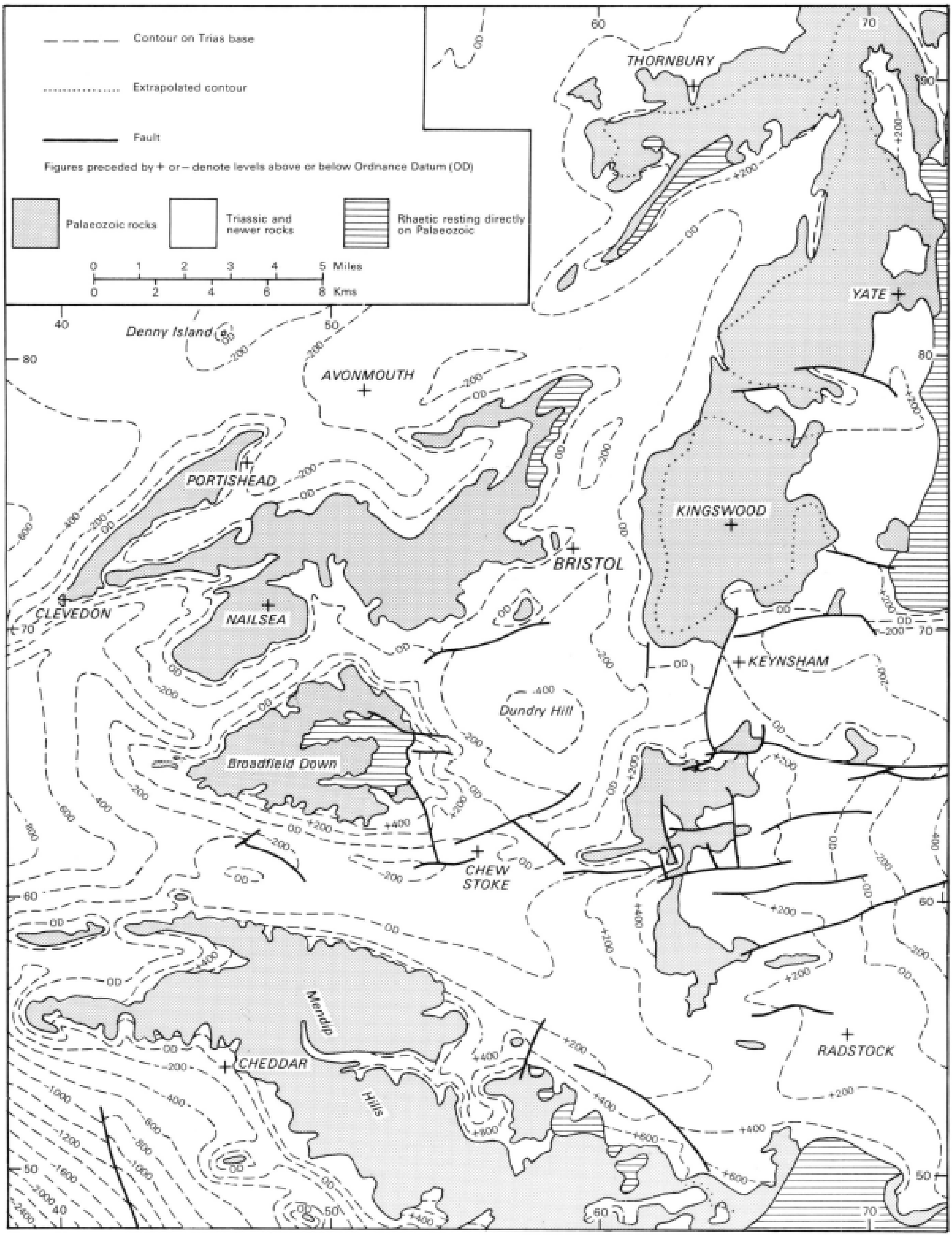


Figure 23 Generalised contour map for the elevation (m OD) of the base of the Mercia Mudstone Group (from Kellaway et al., 1993). British Geological Survey © UKRI 2018

Rock type descriptions

The topmost unit of the Mercia Mudstone Group is the Blue Anchor Formation. This formation, previously known as the 'Tea Green Marl', typically comprises pale green-grey, dolomitic, silty mudstones and siltstones with thin argillaceous or arenaceous laminae and lenses and a few thin, commonly discontinuous, beds of hard, dolomitic, pale cream to buff, porcellanous mudstone and siltstone. Along the north Somerset coast is an upper unit of grey, black, green and, rarely, red-brown dolomitic mudstones with some yellowish-grey dolostones. This upper unit is poorly developed north of the Mendip Hills. The Blue Anchor Formation is around 7 to 9 m thick in the Worcester basin, 2 to 5 m around Bristol, but absent over the Mendip Hills. South of the Mendip Hills it thickens markedly to around 20 to 40 m thick in the Bristol Channel basin, thins to 7 to 12 m in the Wincanton area, and thickens again to over 60 m further south in Dorset.

The base of the Blue Anchor Formation is marked by an abrupt colour change to the red mudstones of the Branscombe Mudstone Formation. This unit consists of red-brown mudstone and siltstone, with common grey-green reduction patches and spots. The mudstones are mostly structureless, with a blocky weathering habit. Gypsum/anhydrite, locally of economic importance, is common throughout in beds, nodules and veins. In the Bristol and Gloucester region, the celestite-rich Yate Evaporite Bed is 10 to 15 m below the top of the formation. Sporadic thin beds of argillaceous sandstone and silty dolostone occur in the lower part of the formation. In south Devon, Somerset and Gloucestershire, the highest 10 to 20 m of the formation include common beds of greenish grey mudstone, giving rise to markedly colour-banded sections where exposed in coastal or river cliffs.

Below the Branscombe Mudstone Formation is the Arden Sandstone Formation, which consists of pale grey sandstone interbedded with mainly greenish grey mudstone. Sandstone is a distinctive component of the formation but the thickness and proportion of sandstone varies considerably from place to place. The formation is typically 7 to 8 m thick in the Worcester basin, rising to 20 m in the BGS Stowell Park Borehole towards the south of the Worcester basin, and 24 m on the south Devon coast.

The lowest part of the Mercia Mudstone Group is the Sidmouth Mudstone Formation. This consists dominantly of red-brown mudstone and siltstone with common grey-green reduction patches and spots. The mudstones are mostly structureless, with a blocky weathering habit, but units up to 15 m thick of interlaminated mudstone and siltstone occur in parts of the formation. The Redcliffe Sandstone Member, a distinctive, deep red calcareous and ferruginous sandstone, is a marginal facies of the formation developed locally in the Bristol area (Kellaway et al., 1993). Up to 30 m of halite is present in in the central Somerset basin between the Quantock and Mendip Hills structural highs (Somerset Halite Member). This was proved in the BGS Burton Row Borehole at depths of 693 to 742 m, and between 183 and 219 m in the Puriton Borehole. The distribution of halite is related to major faults in the underlying Variscan basement that gave rise to differential subsidence during the deposition of the Mercia Mudstone Group. Gypsum/anhydrite also occurs throughout the formation as nodules and veins.

4.2.2 Older sedimentary rocks

4.2.2.1 WARWICKSHIRE GROUP (INCORPORATING THE GROVESEND FORMATION) — LSSR

The late Carboniferous Warwickshire Group (formerly the ‘Upper Coal Measures’) comprises a diverse assortment of mudstone, siltstone, coal and sandstone of Westphalian D and Stephanian age (Figure 24). These largely terrestrial deposits were laid down in freshwater, fluvial and overbank environments, with sporadic marine incursions that can be used for correlation. The variable nature of the depositional environment means that there are significant thickness and facies changes across the region.

Variscan (late Carboniferous–Early Permian) deformation has isolated previously contiguous Coal Measures strata, including the Warwickshire Group strata, into a number of distinct areas or basins in the Bristol–Somerset area (Figure 25). These sub-basins have varying thicknesses of strata preserved to different depths. The Bristol coalfield includes the Kingswood Anticline and Coalpit Heath Syncline to the east and north-east of Bristol respectively, while the Somerset coalfield comprises the Pensford and Radstock synclines to the south-east (Figure 25). The Avonmouth and Nailsea synclines contain coal basins that are structurally distinct, although linked to the major coalfields in the subsurface. The Forest of Dean coalfield is a structurally separate basin, isolated in a distinct synclinal structure.

Due to the complex Carboniferous basin evolution and phases of subsequent basin inversion and tectonic deformation, the late Carboniferous strata are highly variable in thickness and present at a variety of depths across the area (Figures 24 and 26). They are also largely covered by younger rocks; about 73 per cent of the Bristol and Somerset coalfield area is concealed beneath Mesozoic strata.

In the Bristol and Gloucester region, the Warwickshire Group can be divided into two distinct units: the Grovesend Formation, a PRTI, and the Pennant Sandstone Formation, not a PRTI (Figure 24). Although the Grovesend Formation has not been modelled as a separate unit, the extent of the Grovesend Formation within the depth range of interest is based upon structural contours and isopachyte maps in the Bristol special sheet memoir (Kellaway et al., 1993). The Grovesend Formation totals around 900 m in thickness and is divided into four members. In the Coalpit Heath Syncline (Figure 25), the base of the Grovesend Formation reaches an approximate maximum depth of around 300 m. It is only in the centre of the Coalpit Heath Syncline that the lower part of the Grovesend Formation is likely to be at the required depth.

In the separate Forest of Dean coalfield, the Grovesend Formation is about 340 m thick and restricted to the centre of the syncline. Again, it is only in the centre of the basin that lower part of the Grovesend Formation is likely to be at the required depth.

Further south, in the more deformed Somerset coalfield, the base of the Grovesend Formation is likely to reach the required depths in the Radstock and Pensford coal basins (Figure 25; Figure 26) at approximately 600 m depth. It will also be at the required depth in the southern part of the Somerset coalfield adjacent to the Mendip Hills. However, this part of the coalfield is structurally very complex and is cut by many faults, including major thrust faults such as the Farmborough fault belt and the Radstock Slide Fault. In places the strata are overturned. The thickness of the Grovesend Formation in the Severn basin is approximately 160 m and up to 330 m thick in the Nailsea basin (Figure 25).

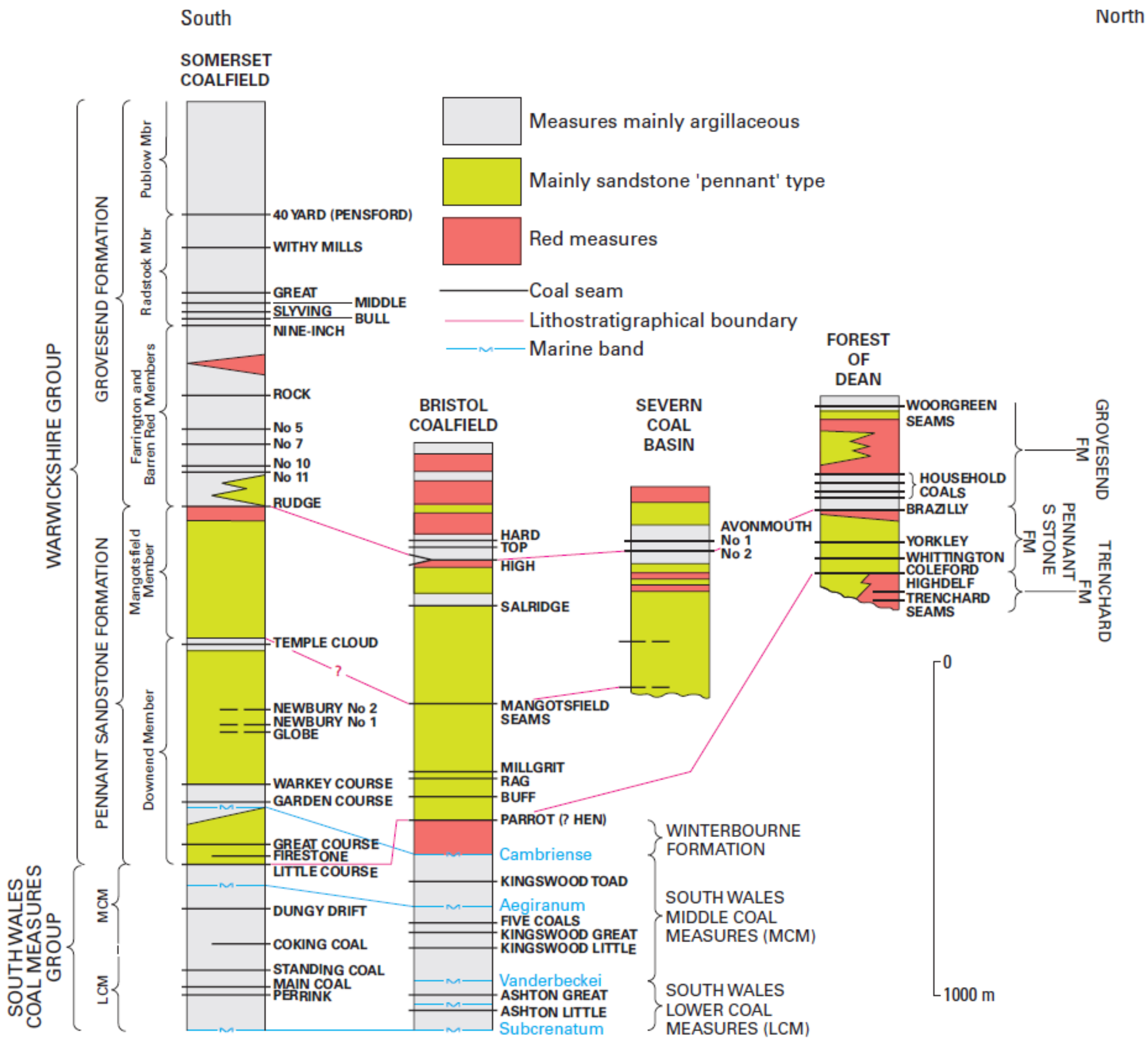


Figure 24 Generalised sections of the Warwickshire Group from the Somerset, Bristol, Severn and Forest of Dean coalfields (from Green, 1992). British Geological Survey © UKRI 2018

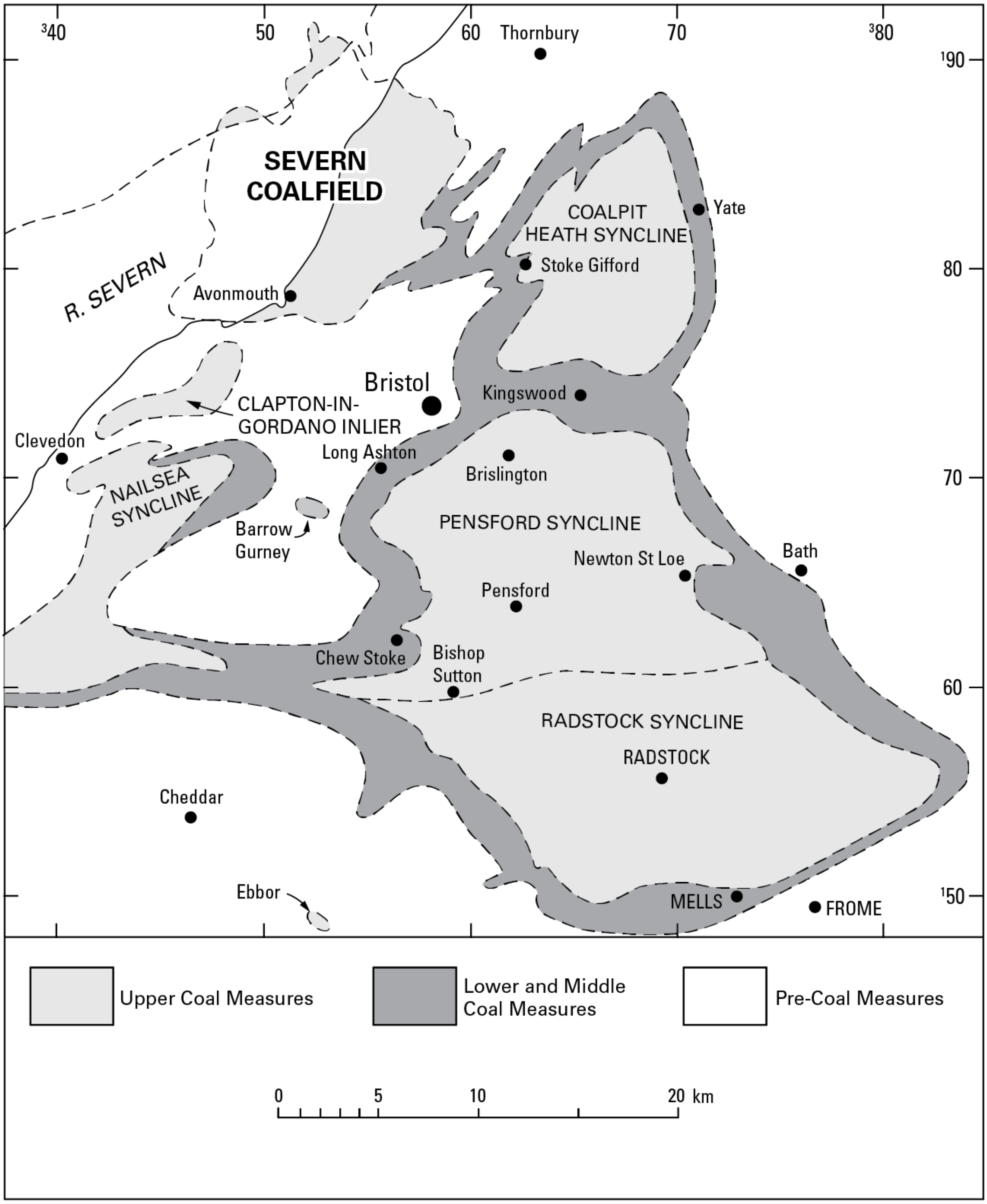


Figure 25 The distribution of the late Carboniferous Warwickshire Group (formerly the 'Upper Coal Measures') coal basins in the Bristol–Somerset region (from Kellaway et al., 1993). British Geological Survey © UKRI 2018

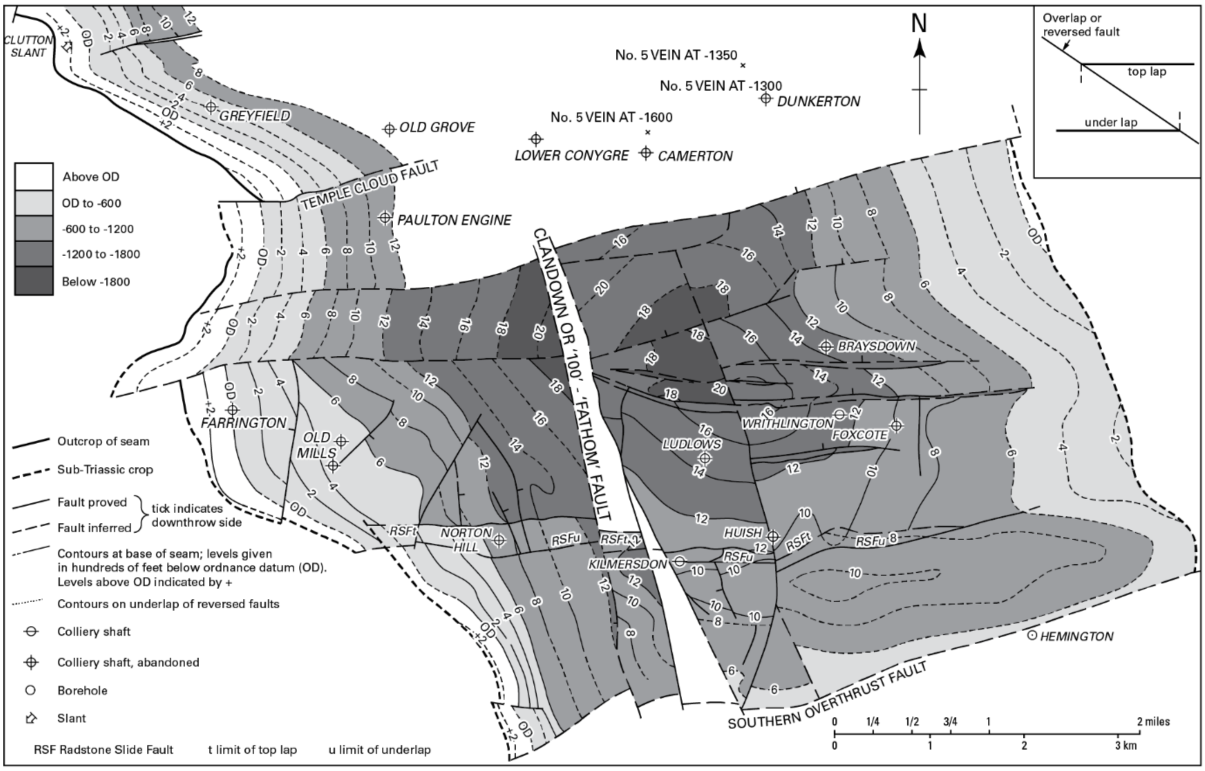


Figure 26 Structure contours on the No. 5 (Middle Vein) coal seam of the Farrington Member (the lower part of the Grovesend Formation) in the Somerset coalfield (Radstock area). From Kellaway et al., (1993). British Geological Survey © UKRI 2018

Principal information sources

The Warwickshire Group in the Bristol and Gloucester area is known primarily from historic coal mining records, mine shafts and deep boreholes. A list of the coal mine shafts and deep boreholes are documented in Kellaway et al. (1993). The surface outcrop of the Grovesend Formation is generally on low-lying ground and poorly exposed. Details of the group are documented in Kellaway et al. (1993) and Green (1992). Local details are provided in the 1:50 000 map sheet geological memoirs.

Rock type descriptions

The Grovesend Formation is composed predominantly of grey mudstones and siltstones, with many thin coal seams, interbedded with mottled red mudstones devoid of coal seams ('barren' measures). There are subordinate, though locally thick, lithic sandstones present. The formation can be divided into four units. From youngest to oldest these are the Publow, Radstock, Barren Red and Farrington members. The Publow Member is characterised by up to 600 m of grey mudstone and siltstone, with subordinate sandstone and rare thin coals. The sandstones are typically of lithic arenite (pennant type), but also include massive quartzose sandstones. The Radstock Member consists of grey mudstone and numerous thin, muddy coal seams, and is up to 315 m thick in the Pensford Syncline and 250 m in the Radstock Syncline (Figure 25). The Barren Red Member consists of red and grey mottled mudstones and siltstones and some lithic sandstones lacking workable coals. It is between 230 m thick in the Radstock Syncline and 275 m thick in the Coalpit Heath Syncline. The Farrington Member consists of grey mudstones with sporadic thin sandstones and numerous thin coals. It varies in thickness from 425 m in the Radstock Syncline to less than 60 m in the Bristol coalfield.

4.2.3 Basement rocks

4.2.3.1 UNDIVIDED DEVONIAN ROCKS — HSR

Devonian outcrop in the Bristol and Gloucester region is divided into five main areas; to the west of the Severn Estuary; in the central north around Thornbury in the west to Wickwar in the east; in the central south from to the west of Bristol to the coast; in the south, between Weston-super-Mare in the west to Bruton in the east; and in the extreme south around Othery. Only the latter two areas, both occurring in the south of the region, lie within the established Variscan cleavage belt and therefore are identified as HSR PRTIs (Figure 8) and are described below.

The most northerly of these PRTIs, encompassing four polygons lying between Weston-super-Mare in the west to Bruton in the east, comprises the Portishead Formation. The extent of this area of HSR is very poorly known, and is related to the top of a thrust culmination/periclines in the subsurface. The only available data on the nature of the succession comes from the Norton Ferris Borehole, which proved red-green mudstones and marls, red siltstones and red-yellow, hard, fine-grained quartzose sandstones, with conglomerate locally. The nature of the succession below the base of the borehole is not known and part of the succession within the depth range of interest may be mudstone dominated. If so, the area falls within the Variscan cleavage belt. It is therefore retained as a PRTI.

In the extreme south, the most southerly area of Devonian HSR PRTI are considered an extension of the South-west England Devonian HSR lithologies immediately to the west. There the outcropping section comprises Upper and Middle Devonian rocks, specifically the Upper Morte Slates Formation, Ilfracombe Slates Formation and Hangman Sandstone Formation, although they are at depth within the Bristol and Gloucester region and have not been interested by a borehole within the region.

4.2.3.2 UNNAMED SILURIAN TO DEVONIAN MAFIC EXTRUSIVE ROCKS — HSR

In the Bristol and Gloucester region, volcanic rocks of Silurian age are present in the Moon's Hill inlier on the Mendip Hills near Frome, located in the Beacon Hill pericline (Figure 29), and as two lava flows in the Tortworth area north of Bristol. Both are only known from relatively small outcrops. Very little is known about the lateral and vertical extent of these extrusive bodies, or how widespread they are at depth. The Tortworth lava flows are unlikely to extend to depths > 200 m and are not considered further.

The extent of the Silurian volcanic rocks beneath the east Mendip Hills is very poorly known. Although they are mapped only in the core of the Beacon Hill Pericline, they may also occur in the cores of other Mendip periclines. The extent of the HSR region is guided by the mapped extent of the Beacon Hill, North Hill and Black Down periclines (Figure 29) where the volcanic rocks are thought to form the core — this is derived from the BGS 1:50 000 scale geological maps (Sheets 280 and 281, Wells and Frome). The eastern and western extents of the HSR PRTIs (Figure 8) are very poorly constrained.

Principal information sources

The Moon's Hill volcanics are well exposed in a large quarry south of Stoke St Michael, and at other smaller, disused quarries along strike, within the Beacon Hill Pericline (Figure 29). They are described by Green (2008). The Tortworth volcanics are known from geological mapping and are described in Kellaway et al. (1993). Both sites are documented in the regional guide (Green, 1992).

Rock type descriptions

The Moon's Hill extrusive rocks comprise a thick series of very steeply dipping or overturned, interbedded lavas, tuffs and volcaniclastics, which comprise part of a large volcanic centre of unknown extent. The Moon's Hill volcanics comprises an interbedded succession of andesite and rhyodacite lavas, rhyodacite tuffs and volcaniclastic conglomerates. The thicknesses of the individual units are highly variable but the total thickness of the volcanic rocks is over 500 m, thickening eastwards to 700 m. The source of the volcanic material is thought to be an important volcanic centre lying nearby to the east or north-east of the Moon's Hill inlier.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in the Bristol and Gloucester region and shows their surface extent on a map (Figure 30). Many of the structures are well known and are identified in the BGS regional guides and memoirs. As described in the guidance (RWM, 2016a), they are relevant to safety in two ways: they may provide effective limits to any rock volume being considered for siting a GDF, and they have an impact on the uniformity and predictability of rocks and groundwater at a scale of relevance to a GDF.

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

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

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

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

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

5.2 REGIONAL TECTONIC SETTING

The surface and subsurface structure of the Bristol and Gloucester region can be described in terms of four major structural events (orogenic cycles) that affected the region and surrounding areas: the Avalonian, Caledonian, Variscan and Alpine orogenies (see Pharaoh and Haslam, 2018). Between these compressional events there are phases extension and basin formation. Distinct structural and sedimentary rock 'units' are associated with the compressional and extensional events. The name of key structures and faults are highlighted in *italics* at first usage in the text.

For the purposes of this report it is useful to refer to groups of strata as follows:

- younger cover (Permo-Triassic to Cretaceous)
- older cover ('foreland' Carboniferous, north of the Variscan front (Figure 27)
- Variscan basement (deformed Precambrian to Carboniferous, south of the Variscan front)
- Caledonian basement (Precambrian to early Palaeozoic rocks as basement to older cover north of the Variscan front)

Knowledge of the pre-Carboniferous, Caledonian earth movements within the region is poorly understood due largely to the restricted outcrop of the older rocks, but they are indicated by an important unconformity between Silurian (late Llandovery) and Cambrian rocks in the Tortworth area and by an appreciable pre-Late Devonian (Farlovian) unconformity. In the latter, pre-Farlovian strata have undergone horst-type uplift and erosion aligned in a north–south direction, most notably in the central part of the uplifted region. Due to the cover of later rocks, only the western side of the structure, comprising the Berkeley Fault, is clearly seen, with a pre-Farlovian downthrow to the west of some 600 m (Cave, 1977; Green, 1992). Apart from this uplift, the early Palaeozoic rocks of the Tortworth inlier are generally more faulted and folded than the adjacent Carboniferous rocks.

South of the Tortworth area, the Upper Old Red Sandstone Group in the eastern Mendip Hills rests directly on Silurian (Wenlock) strata with a low angular unconformity, and it has been suggested that the two areas lie on a north–south axis of uplift related to the Malvern 'line', 'lineament' or 'axis' (Figure 27); the latter term is adopted in this document. This structure has long been regarded as one of the fundamental structural elements of the region and represents an ancient Avalonian (Neoproterozoic) terrane boundary within the Midlands microcraton, separating late Precambrian volcanic and associated sedimentary rocks forming the Wrekin and Charnwood terranes (Pharaoh et al., 1987a; Lee et al., 1990; Smith et al., 2005). Based upon geophysical, mainly magnetic, data, this structure is thought to extend southwards from the Welsh Borderland region to the north into the region as far south as the Variscan front and possibly beyond. The 'Malvern axis' is named after the narrow, elongate, north–south trending horst of Precambrian igneous and metamorphic rocks forming the Malvern Hills and which has been the site of uplift and reverse faulting at various intervals since Precambrian times.

A north-east structural trend, known as the 'lower Severn axis' (Figure 28), is present to the north and north-west of Bristol, ultimately merging to the north with the north–south trending Malvern axis structures. This reflects the north-east trend arising from the Acadian Orogeny that formed Wales' main structural grain and imposed a series of largely north-east-trending, periclinal folds and faults across much of the adjacent Wales and Welsh Borderlands regions. Farther north-west, in the Monmouth–Forest of Dean area and opposite to the north-east trend, a series of folds and some faults produce a more north-west to south-east trend, becoming northerly the further north they are traced. The structures extend westwards into the adjacent Welsh Borderland region and probably represent the complex interaction of the (dominant) north–south Malvernoid trend and the north-east Welsh Acadian trend in the Bristol and Gloucester region during the Caledonian and Variscan orogenic events.

The Variscan Orogeny, which culminated at the end of the Carboniferous, represents the most visible and severe deformational event to have affected the rocks of the Bristol and Gloucester region that now spans the Variscan front. To the south of the front, Devonian and Carboniferous rocks are folded, commonly cleaved and thrust faulted along dominantly east–west lines, forming the Variscan fold belt (e.g. Hancock et al., 1983; Kellaway and Hancock, 1983). The major structural trend imparted by the Variscan Orogeny follows a west-north-west trend across the Bristol Channel into the adjacent south-west England and Wales regions. The large-scale folding and the development of several major, generally east–west-trending, southward-dipping thrust zones (such as the Variscan Frontal thrust (Figure 27)) in this region and the Portland–Wight Thrust to the south in the adjacent Hampshire Basin region) are imaged on seismic reflection profiles. The thrusts are roughly planar to a depth of at least 15 km, beneath which they may lose their identity on seismic reflection data within the lower crust (Chadwick et al., 1983; Chadwick and Evans, 2005).

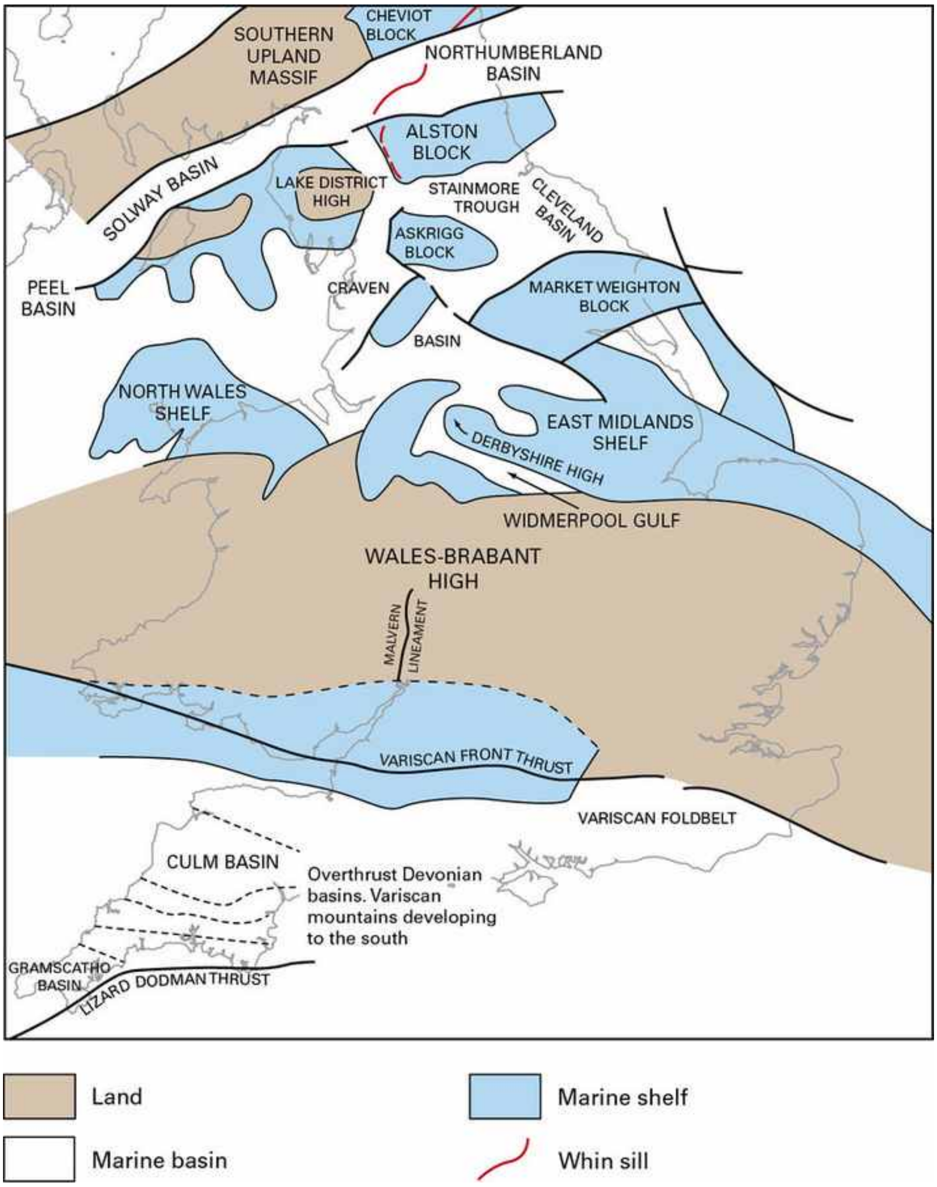


Figure 27 Blocks and basins of the Carboniferous.

The thrusts as imaged on seismic data are defined by a zone of southerly-dipping reflections up to 2 km thick and must arise from a series of structures such as an anastomosing network of subparallel fault strands rather than a simple structural interface (Chadwick and Evans, 2005). The main Variscan Frontal Thrust (Figure 27) dips to the east-south-east from about 4 to 9 km below ground level with a true dip of circa 29º and is a sole thrust to overlying structures. One of these, the Wardour Thrust, has a similar seismic appearance to the main Variscan Frontal Thrust (Figure 27), with a zone of subparallel reflectors some 1.5 km wide dipping southwards, but with a lower dip of about 20º. To the west, a similar thrust, the Somerton Thrust, has been identified on seismic data dipping south-south-west at about 28º (Donato, 1988). However, the minimum depth of the Somerton Thrust is unknown and has only been imaged on seismic at depths greater than 1000 m bgl. It is uncertain how the Somerton, Cannington Park and Wells thrusts and the Emborough Thrust–Southern Overthrust (Figure 29) relate to structures along strike and many may be linked to form longer structures, traceable over a distance in excess of 140 km, continuing west beneath the central Bristol Channel (Brooks et al., 1988), beneath Exmoor and the north Devon Anticline (Chadwick et al., 1983; Donato, 1988; Chadwick and Evans, 2005) and east into the neighbouring Hampshire and Wealden regions. These thrusts underlie important Mesozoic extensional structures and are likely to be different segments of the same thrust complex and, together with other thrusts, lie above the Variscan Frontal Thrust, and probably represent an imbricate thrust stack or imbricate fan (compare with Boyer and Elliot (1982)).

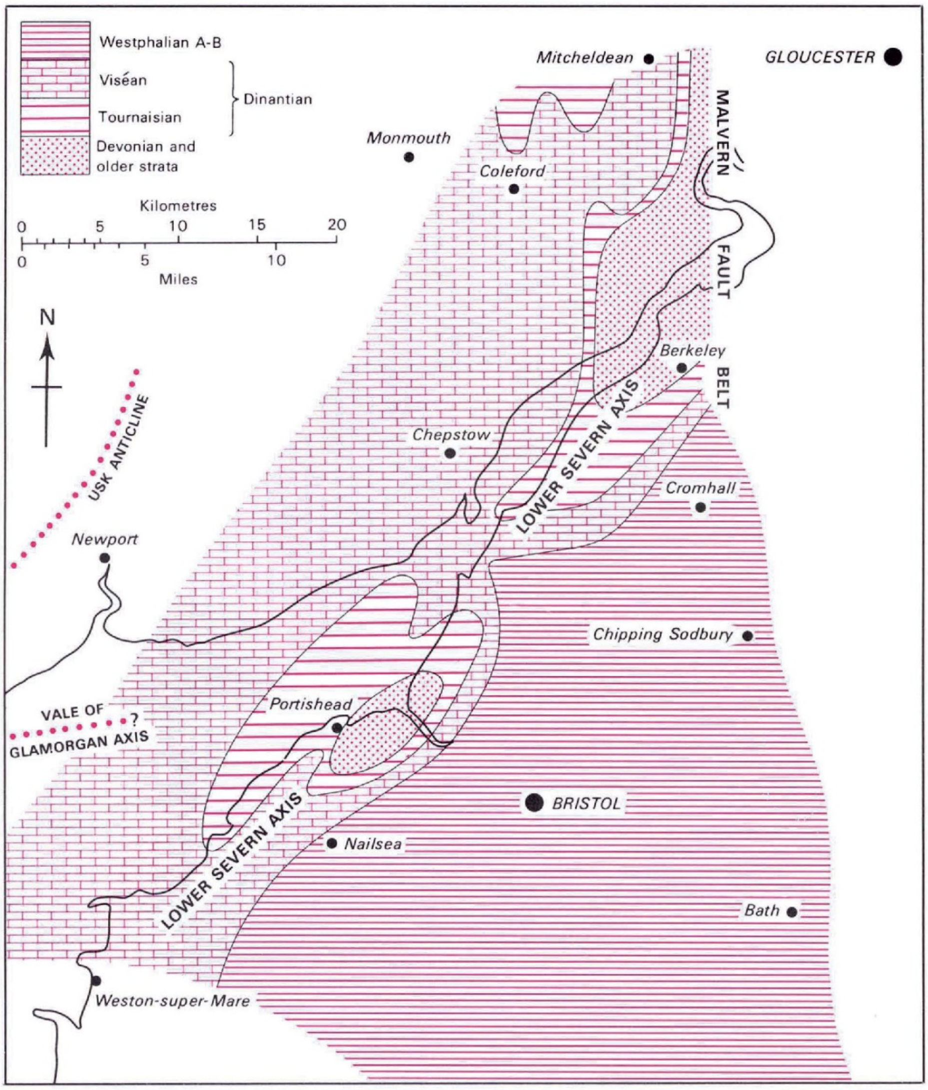


Figure 28 Position of Severn axis in relation to the Malvern axis ('Malvern fault belt' on this image). British Geological Survey © UKRI 2018

Westwards along strike from the Variscan Frontal Thrust, basement rocks in the Mendip Hills are strongly folded into a series of *en echelon*, asymmetrical periclines with steep, sometimes overturned and thrust-faulted northern limbs (Green and Welch, 1965). The periclines are associated with a number of east–west-trending, southerly dipping thrusts, which form a prominent belt of thrusting that appears to correlate with the imbricate thrust stack noted previously. The Blackdown Pericline (Figure 29), for example, is a large, asymmetrical hanging-wall anticline associated with the Farmborough fault belt.

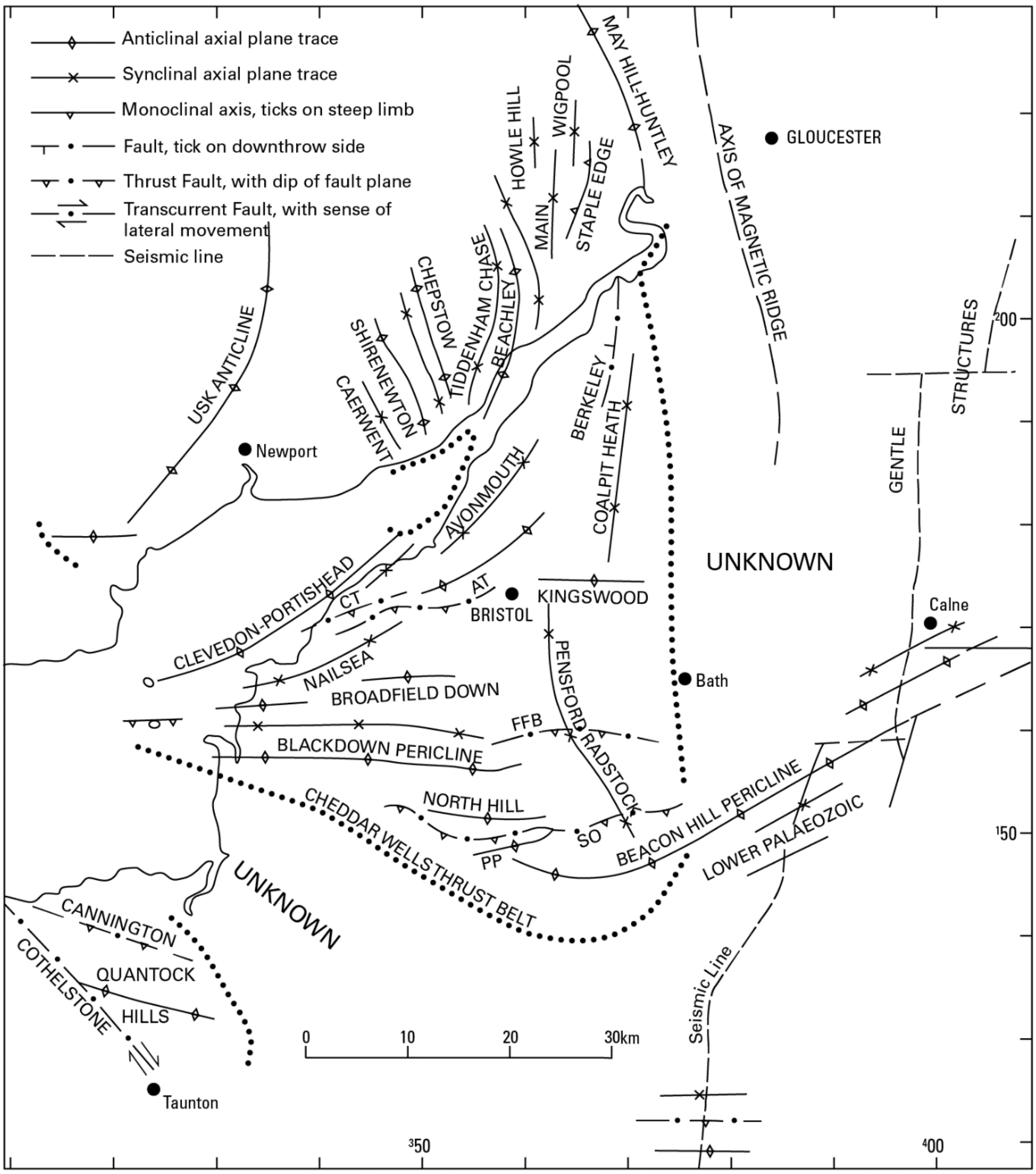


Figure 29 Major structural features in the Palaeozoic rocks of the region to the west as far as the Usk Anticline. AR = Avon Thrust, Ct = Clevedon Thrust, FFB = Farmborough Fault Belt, PP = Pen Hill Pericline, SO = Southern Overthrust, Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

Thus the late Variscan movements resulted in a south-to-north translation with overfolding and north-verging imbricate thrust faulting. To the north of the front, an area between Belgium and south-west Wales formed the Variscan foreland, across which a chain of late Carboniferous Coal Measures basins developed, linked to the rising Variscan fold belt to the south. Continued northerly propagation of the Variscan thrusts meant that, with time, the more southerly basins gradually became included and incorporated as part of the deformed fold-belt area. Consequently, whilst the rocks of the foreland area are much less disturbed and the putative line of the Variscan front marks the northern limit of pervasive deformation, no simple east–west front can be defined in the Bristol and Somerset coalfields without excluding large areas of faulted and deformed rocks to the north (Kellaway and Hancock, 1983). This picture is further complicated by the presence and effects of pre-existing faults associated with the north–south Malvern axis (shown as Malvern Fault Belt on Figure 28).

These Variscan movements were, therefore, largely responsible for, and gave rise to, the main structural elements in the south of the region, many of which also controlled the subsequent Mesozoic and Cenozoic structural development of the region. During the Mesozoic, a number of the Variscan thrusts were reactivated in extension resulting in the formation, through normal 'short-cut' faults that link at depth to the Variscan thrusts, of a series of sedimentary basins across southern England. Within these basins, which just impinge upon the very south of the Bristol and Gloucester region from the Hampshire Basin region to the east, thick sequences of younger cover rocks were deposited. To the north of the Variscan front, north–south basement structures were also reactivated and formed the important Worcester and Knowle basins, within which great thicknesses of younger cover rocks were deposited (Chadwick and Smith, 1988; Chadwick and Evans, 1995; 2005). Cenozoic compression related to the Alpine Orogeny resulted in reactivation of the extensional faults and the formation of a series of linear and curvilinear fold belts and monoclines in the younger cover strata.

5.3 MAJOR FAULTS

This section briefly describes the main fault zones in the Bristol and Gloucester region as they affect the younger and older cover rock units. The major faults, selected from analysis of the UK3D model and published maps in the region (Figure 30), exhibit a variety of orientations with many being reactivated both in extension and compression as a consequence of the complex structural history described previously and in Pharaoh and Haslam (2018).

Structures developed during the Caledonian and Variscan orogenies played a significant role in the post-Variscan evolution of the region, particularly south of the Variscan front. In this description, the major faults are described in terms of crustal 'domains'. Each domain contains a set (or plexus) of faults with a dominant orientation, usually reflecting the influence of structural control from the underlying basement, and, frequently, a comparable displacement history, reflecting the behaviour of similarly orientated fault planes to extension or compression in the contemporaneous regional stress field.

The Bristol and Gloucester region can be divided into two structural domains: one to the north of the Variscan front and one to its south. (Figure 27). The various Variscan faults and folds have been reviewed in detail (e.g. Kellaway and Hancock, 1983), the purpose of this account being to provide a general summary of the structures.

In addition to the faulting, folding that is directly related to faulting, e.g. an anticline associated with a reactivated 'blind' fault or as fault drag on the flanks of the fault, is mentioned along with the controlling fault in the subsequent descriptions. Folding associated with thrust faults or the inversion of extensional faults is described in a separate section following the description of the faulting.

5.3.1 Structures north of the Variscan front

The main basement and structures developed during the Variscan Orogeny have controlled the later location and development of Mesozoic extensional and Cenozoic compressional structures.

To the north of the Variscan front, much of the region is underlain by the Midlands microcraton. Northerly (Malvernoid) trends dominate across approximately the northern two thirds of the region, with major, *en échelon*, normal fault zones forming the Malvern axis that are traced northwards into the 'central area' of the adjacent central England region (Figure 27). South of and immediately to the north of the Variscan front the structural trend is more east–west with a series of thrusts affecting folds within the coal basins. However, structures with a north-east trend occur in the region of the River Severn and Severn estuary and immediately onshore to the south-east, forming the lower Severn axis of Green (1992) (Figure 28). In addition, west of the Severn river and estuary (in the Forest of Dean and Monmouthshire area, in the north-west of the region) north-west to north-north-west trends are encountered, changes that appear to be related to increasing distance from the main Variscan fold belt and illustrating the increasing influence of inherited basement structures similar to those in the Wales region.

The Malvern axis is a fundamental basement structure comprising, in the main, a series of easterly dipping faults. The lineament has a mapped length exceeding 117 km and is believed to have originated in late Neoproterozoic times as a suture zone between two crustal terranes of contrasting crustal composition and history: the Wrekin and Charnwood terranes (Pharaoh et al., 1987b; Pharaoh and Carney, 2000; Smith et al., 2005). It is traced across the region from the Variscan front in the south, northwards into the Welsh Borderland and central England regions. In the Malvern Hills, just to the north of the region, the Precambrian basement is overthrust westward across coevally folded Silurian and Devonian strata. Furthermore, in the Abberley Hills, intense folding of latest Westphalian strata (Dunning, 1992) illustrates the Variscan age of this inversion. To the east an opposing, concealed, westerly dipping thrust is now known to be present, imaged on seismic reflection data: this is the Oxfordshire (Alcester) Thrust (Barclay et al., 1997; Chadwick and Evans, 1995; 2005).

Faulting of the younger cover reflects largely extensional phases in Permian to Jurassic, and probably Cretaceous, times. During these times, basement thrust faults were reactivated, which led to the collapse of the hanging-wall block as a series of steeper, 'short-cut' normal faults developed. The most important faults formed the margins to the Worcester and Knowle basins complex, which extends across the region and includes smaller sub-basins such as the Weethley basin, in which younger cover sediments accumulated. The main controlling structures to the basins are the easterly dipping Malvern axis (reverse/thrust) faults and the opposing, westerly dipping Oxfordshire (Alcester) Thrust which, respectively, controlled the development of the western and eastern basin boundary. Several more north–south intrabasinal faults also developed.

In the north, seismic lines image the main western basin-controlling faults as low-angle, down-to-west, easterly dipping thrusts or reverse faults inverted during the Variscan Orogeny and subsequently reactivated in extension during the Permian, forming hanging-wall, short-cut faults and the Worcester basin (Chadwick et al., 1983; Chadwick and Smith, 1988; Barclay et al., 1997). These short-cut faults have up to 2500 m of normal displacement and are usually synthetic to the underlying thrust, though significant antithetic normal faulting can occur. The main normal faults and fold structures include the East Malvern, Donnington–Huntley and Blaisdon faults, defining the western margin of the Worcester basin, and, continuing south, the Huntley Anticline, the Berkeley Fault and the Coalpit Heath Syncline (Figure 25). The series of structures have been termed the Malvern fault belt (Kellaway and Hancock, 1983). The normal, down-to-east East Malvern Fault, forming the eastern boundary fault of the Malvern horst and the western limit of the younger cover in the Worcester Basin (Figure 5) is the clearest example of the extensional reactivation of the Malvern thrust system during Mesozoic times. It is mapped over a length of around 75 km in the adjacent central England region, with over 600 m displacement in UK3D, and is traced around 11 km into the north-west of the region. The southwards continuation of the East Malvern Fault is not clear at the surface, but is possibly concealed east of the Tortworth inlier, along a gravity gradient, which runs through Wotton-under-Edge and extends south as the Bath axis. *En échelon* and stepping the graben margin westwards are the Donnington–Huntley (>15.5 km long, >730 m east downthrow) and Blaisdon (>18.5 km long, >200 m east downthrow) faults, the latter terminating around the River Severn.

A series of offset, north–south faults mapped at the surface but with smaller apparent displacements continue south from the Berkeley Fault, reflecting the inferred, continued-southwards presence of this Malvern axis at depth beneath the region.

Concealed beneath the Mesozoic cover in the north-eastern margins of the region is the Oxfordshire (sole) Thrust (also termed the Alcester Thrust: Barclay et al., 1997), a complex, compressional basement structure forming an opposing, mirror image of the Malvern axis structures with a displacement greater than 500 m (Chadwick and Evans, 2005). The structure is imaged on seismic lines as a westerly dipping, easterly downthrowing thrust, which was also reactivated during Mesozoic extension and controlled the development of a series of north–south, down-to-west normal faults defining the eastern margins of the Worcester graben and the Knowle basin (Chadwick and Smith, 1988; Chadwick and Evans, 1995, 2005): these faults are the Inkberrow–Lickey End, Weethley, Gloucester and Moreton–Ilmington–Preston–Aston Grove faults.

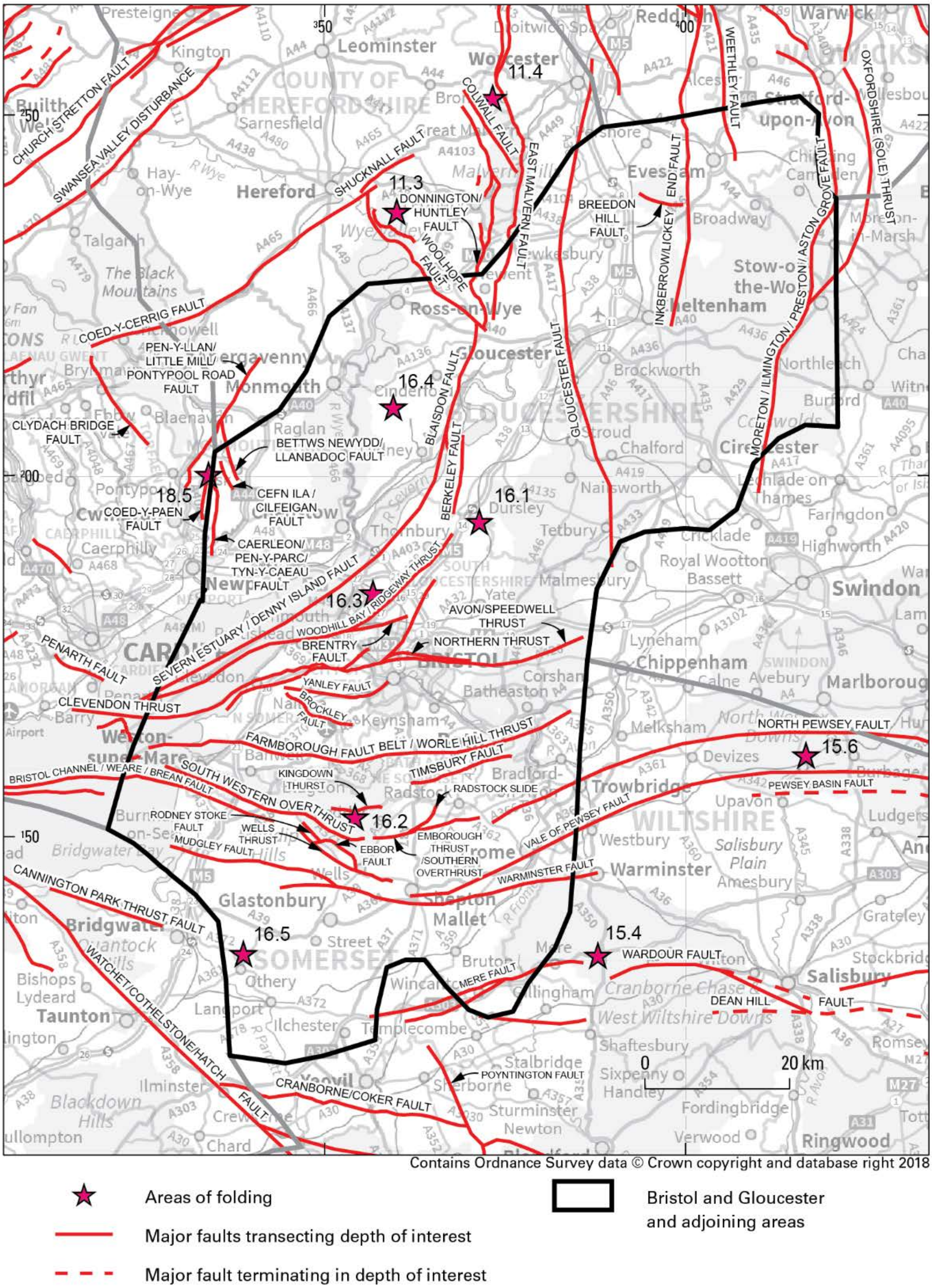


Figure 30 Major faults and areas of folding in the Bristol and Gloucester region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

The Inkberrow–Lickey End Fault is mapped over 58 km, with up to 1050 m of Early Triassic syndepositional normal displacement and about 200 m normal downthrow in Triassic–Jurassic strata (Chadwick and Evans, 2005). The fault has its origin near the Lickey Hills, where the Worcester graben terminates and transfers to the Knowle basin, and was imaged on the Stratford seismic profile (Chadwick and Smith 1988). The Weethley Fault has a mapped length greater than 22 km as a down-to-west normal fault, with about 1000 m downthrow and forming the eastern margin of the Worcester graben. The normal, down-to-west Gloucester Fault has a mapped length of 71 km with 590 m displacement of Triassic strata. The most easterly of the main north–south fault zones in the region is the mixed sense of throw, braided, normal, down-to-west Moreton–Ilmington–Preston–Aston Grove Fault (also known as the Clopton Fault; Chadwick and Evans, 1995), which is also imaged on the Stratford seismic profile (Chadwick and Smith 1988). It is mapped over a length of almost 50 km with a displacement exceeding 400 m in UK3D and possibly over 1300 m at the base Permo-Triassic levels (Chadwick and Evans, 1995).

The Berkeley Fault to the south is a north–south-trending, high-angle, easterly dipping reverse fault, lying to the east of the Blaisdon Fault and associated with the Malvern axis. It has in excess of 300 m westerly downthrow and, although present in the UK3D model with a length of some 11 km, it is thought to continue to the south-west as the Woodhill Bay–Ridgeway Thrust (lower Severn axis), which runs south of the Severn estuary to the Variscan front (Kellaway et al., 1948). The Woodhill Bay–Ridgeway Thrust dips to the east (Barton et al., 2002), is some 29 km in length and extends north-east to near the Berkeley Fault, with over 355 m down-to-west throw in UK3D. It developed as a synsedimentary fault during late Visean to mid-Westphalian times, inversion and reverse faulting having taken place during the later phases of the Variscan movements (Kellaway and Hancock, 1983). To the west and offshore in the River Severn runs the Severn Estuary–Denny Island Fault, a sinistral strike-slip fault with more than 3 km displacement (Barton et al., 2002), which probably comes onshore near the Severn Bridge and extends to join with the Blaisdon Fault.

To the west of the River Severn, in the Monmouth–Forest of Dean area, the north-west to south-east-trending Woolhope Fault is the main fault structure of this trend. At almost 27 km in length it has a vertical displacement of over 310 m in UK3D. On seismic reflection data it is seen to dip to the north-east, the amount of dip decreasing in the subsurface such that it may link with the Malvern axis thrusts at considerable depth. Displacement in the subsurface is considerable but cannot be accurately determined, but is estimated to be at least 900 m down-to-west (Chadwick and Evans, 2005).

It has been suggested that the important strike-slip Severn Estuary–Denny Island Fault, postulated to lie beneath the Severn estuary and analogous to the well-known Vale of Neath and Swansea valley 'disturbances' farther west, separates the two thick coal basins of the South Wales coalfield in the west and the Bristol and Somerset coalfields in the east. This structure runs parallel to the Woodhill Bay–Ridgeway Thrust and would account for major unconformities at the base of the Namurian, within the Westphalian and possibly also within the late Visean (compare with Green, 1992). Folding, uplift, erosion and hence unconformity appear to have been most active at the margins of the area, adjacent to the main coalfields, namely along the Malvern and lower Severn axes in the east (within the region) and the Usk (Figure 25) and Vale of Glamorgan axes in the west. This is most strikingly seen in the Forest of Dean coalfield area (Green, 1992).

5.3.2 Structures of the Variscan front and Variscan fold belt

Across approximately the southern third of the part of the Midlands microcraton that lies within the region, structure is dominated by major, often arcuate, *en échelon* Variscan folds and thrusts of overall west–east trend, which are traced into the adjacent Hampshire Basin and south-west England regions. It is commonly termed the Cheddar Wells thrust belt (Green, 1992). The major thrusts are south-dipping structures, which, together with the asymmetric, north-verging folds (see Section 5.4), have long been interpreted to suggest northward compressional deformation during late Carboniferous to Early Permian times (Barton et al., 2002). The thrusts in the vicinity of the Mendip Hills and Bristol have been described in terms of 'piggyback' thrusting, whereby thrusts propagated from south to north, with later thrusts developed in the footwalls of earlier thrusts, carrying the older thrusts forwards (Williams and Chapman, 1986). There are a number of major thrusts, with smaller subparallel and *en échelon* thrusts also developed, with total shortening across the Mendip belt estimated at 20 km (Barton et al., 2002). As previously alluded to, a series of concealed, southwards-dipping thrusts have been imaged on seismic lines to the east, the most northerly forming the Variscan Frontal Thrust, which lies along strike from the exposed Variscan basement rocks of the Mendip Hills, where similar south-dipping structures come to crop (Chadwick and Evans, 2005).

The main down-to-north thrusts in this region include: the Farmborough fault belt/Worle Hill Thrust, South-western Emborough Thrust–Southern Overthrust, Avon–Speedwell, Ebbor, Kingdown, and Wells thrusts. The Farmborough fault belt is thought to be the westward expression of the Variscan Frontal Thrust imaged on seismic lines to the east, displacement on which is more than 900 m in the late Westphalian strata (Green and Welch, 1965), which probably increases with depth (Chadwick and Evans, 2005). The Worle Hill Thrust has a throw of 300 to 400 m to the north and is associated with overfolding and smaller-scale thrusting in the eastern part of the Weston–Worle Anticline (Whittaker and Green, 1983; see also Section 5.4). The Avon–Speedwell Thrust is the main Variscan thrust hereabouts, extending some 52 km from Clevedon to Bristol and thence eastwards beneath the younger cover, with a displacement of almost 300 m in UK3D. It is associated with smaller subparallel thrusts such as the Clevedon Thrust and the smaller northern thrusts (Barton et al., 2002). A number of sinuous, down-to- south reverse faults are now interpreted as a series of small backthrusts that propagated from the Avon Thrust southwards, including the Brockley and Yanley fault complexes (Barton et al., 2002). The latter fault complex defines the southern edge of an area of relatively simple structure, to the south of which occur highly deformed Coal Measures (Barton et al., 2002).

The southernmost series of *en échelon* faults forming a prominent thrust belt are the South-western Emborough–Southern Overthrust and the smaller Wells and Ebbor thrusts to the south. The South-western Emborough thrust segments have variable displacement of up to 3000 m, merging with the Southern Overthrust and Radstock Slide to the east, the latter having a horizontal displacement of about 500 m and perhaps approaching 1000 m at shallow depths (Chadwick and Evans, 2005). The Wells and Ebbor thrusts are the most southern thrusts, trending north-west to south-east, with lengths of 15.5 km and 8.5 km and down-to-north displacements of 800 m and 400 m respectively. To the north of the main South-western Emborough Thrust–Southern Overthrust, the Kingdown Thrust runs subparallel and downthrows some 300 m to the north (Green and Welch, 1965). A large north-west to south-east-trending, down-to-south, normal fault has previously been mapped in the area between the South-western Emborough–Southern Overthrust and the Wells Thrust, with up to 1500 m displacement: this is known as the Rodney Stoke Fault (Green and Welch, 1965). However, it is not currently modelled in UK3D.

In the extreme south-west, the Cannington Park Thrust just impinges on the region. Although Miliorizos et al. (2004) prefers to model the area without this fault, this south-dipping, east–west-trending thrust fault is mapped between several closely spaced, small inliers north of the Quantock Hills, which expose Carboniferous and Devonian strata (Anderson and Owen, 1968). It is thought to extend into the offshore area north of the Devon coast on the Minehead 50k geological map. With a current mapped length of about 14 km, it is not mapped farther west, but is likely to be present. The throw exceeds 2 km, although it is only 250 m in UK3D.

A series of important, arcuate and *en échelon*, down-to-south, normal fault zones enter the southern and south-eastern areas of the region from the adjacent Hampshire Basin region to the east. The main faults are the Warminster, Vale of Pewsey, North Pewsey and Mere faults. These fault zones comprise 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 Cenozoic inversion. The northern of these faults mark the northern margin of Mesozoic Wessex and Weald extensional basin development and the southern limits of the London–Brabant massif. The faults extend over 165 km from Shepton Mallet in the region, eastwards into the Hampshire Basin and Wealden regions.

The North Pewsey Fault is the most northerly of the Pewsey faults and just impinges on the south-eastern margins of the Bristol and Gloucester region. It has a length of approximately 86 km and a net displacement in places of up to 1000 m. The Vale of Pewsey Fault has a length of over 83 km and a net displacement in places in excess of 1000 m, extending some 24 km into the south-east of the region to the area just south of Shepton Mallet.

The down-to-north Warminster Fault extends across the south of the region as a southern fault to the Vale of Pewsey fault zone. At least 44 km long, it is near vertical for much of its length, with syndepositional movement during part of the Mesozoic (Bristow et al., 1999). This movement appears to have ceased by the Mid Jurassic, as it did not affect Inferior Oolite deposition. The fault underwent mild reactivation during the Neogene (Alpine) compressional events, resulting in reverse throw at crop. Displacement at depth may be over 620 m, whilst estimates at crop indicate variable downthrows to the south and north of between 70 and 30 m, with the fault cutting the Lower Chalk in the Frome district. For more details on this fault zone, refer to Chadwick et al. (1983); Chadwick (1986); Whittaker (1985); Lake and Karner (1987); Bristow et al. (1999), and Chadwick and Evans (2005).

The Mere fault zone extends over 30 km from the south-east across the adjacent Hampshire Basin region and clipping the very southern margins of the Bristol and Gloucester region. 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 displacements at depth and suffered reactivation in extension on a number of occasions. Due to the depth of erosion in the region, evidence for phases of Cenozoic inversion has been removed, but to the east, inversion folds (e.g. the Wardour Monocline) are associated with the fault zone (Barton et al., 2002; Chadwick and Evans, 2005). From UK3D, a maximum normal downthrown displacement to the south of about 520 m is calculated. However, the exact location and nature of the fault becomes less well constrained westwards into the region due to seismic reflection coverage becoming poorer. This fault forms the boundary between the Mere basin, developed to the south, and the southern, updip part of the northerly tilted fault block, forming the Pewsey basin to the north.

In the south-west of the region a number of poorly constrained, down-to-south, east–west-trending normal faults are mapped: the Bristol Channel–Weare–Brean and Mudgley faults. The Bristol Channel–Weare–Brean Fault is a complex, *en échelon* series of east–west-trending faults with an overall length of exceeding 188 km, most of which is mapped offshore. It is thought to extend eastwards and onshore for some 16 km. It has a displacement of over 1300 m in places and was formed as a result of the extensional reactivation of a Variscan thrust (Brooks et al., 1988; Tappin et al., 1994; Miliorizos et al., 2004). The Mudgley Fault is a poorly constrained, east–west-trending fault within the Jurassic outcrop extending some 24 km east from Burnham-on-Sea (Whittaker and Green, 1983). Displacement is hard to ascertain, but from the displacement of the Triassic outcrop is likely to be significant and in the order of 200 m or more.

5.4 FOLDING

Folding is encountered in the Caledonian basement rocks of the Midlands microcraton, e.g. in the Malvern inliers, and some intra-Carboniferous folding also occurred, which produced important unconformities within the Carboniferous strata — most notable in the lower Severn–Malvern axis and in the Forest of Dean coalfield area (Welch and Trotter, 1961). The evidence indicates that the main intra-Carboniferous episode of folding along the line of the lower Severn–Malvern axis was mid-Westphalian in age and is regarded as the first pulse of the main Variscan orogenic movements. Major regional-scale folding represents deformation associated with the main Variscan orogenic event that occurred in later Carboniferous (Stephanian) to earliest Permian times. In the region, the youngest deformed rocks are the Cantabrian Coal Measures of the Forest of Dean and the oldest undeformed rocks are Permian strata proved at depth beneath the Mesozoic rocks of the central Somerset basin.

The region spans the Variscan front, to the south of which Devonian and Carboniferous rocks are folded and thrust faulted along dominantly east–west lines, forming the Variscan fold belt and representing the Variscan basement. To the north of the Variscan front, over the foreland area (the Midlands microcraton), deformation was less pervasive and folding different in nature and style: the rocks of the Variscan fold belt are highly disturbed and commonly cleaved, whilst those of the equivalent age older cover sequence in the foreland are much less disturbed. However, between Belgium and south-west Wales, a chain of late Carboniferous Coal Measures basins developed, linked to that of the rising Variscan fold belt to the south. In the Bristol and Gloucester region these comprise the Forest of Dean, Bristol–Somerset, Severn and Oxfordshire coalfields. These are affected by fold and thrust structures that reflect the gradual incorporation of former foreland areas into thrust sheets as the Variscan front advanced northwards in a series of imbricate stacks. Consequently it is difficult to accurately define the Variscan front, which is here taken as the Farmborough fault belt and the likely westwards projection of the major Variscan Frontal Thrust imaged on seismic lines to the east (e.g. Chadwick and Evans, 2005).

Structures relating to Cenozoic earth movements are generally absent or of negligible effect.

5.4.1 Intra-Carboniferous folding

Intra-Carboniferous folding is observed along the lower Severn–Malvern axis and in the Forest of Dean coalfield areas. Folding, and hence angular unconformity, is most strikingly shown in the Forest of Dean (Green, 1992), where two groups of co-axial folds are present: one pre late Westphalian, the second post late Westphalian in age (Kellaway et al., 1948; Welch and Trotter, 1961; Kellaway and Hancock, 1983). The structures are of lesser magnitude compared to the later folds of the main, end-Carboniferous, Variscan orogenic event.

5.4.2 Folding related to the main Variscan orogenic event

The main folds affecting the Palaeozoic rocks in the region arise from the main Variscan orogenic event and for the purposes of this report, are described in five main groups and shown on Figure 30:

- North–south (Malvernoid) — includes the Bath axis, mainly north of the Variscan front, but with expressions to the south
- East–west (Variscan) — the main components of the 'Cheddar Wells thrust belt', to the north and south of the Variscan front
- North-east to south-west — the Lower Severn axis, north of the Variscan front
- North-north-west to south-south-east — Forest of Dean and Monmouthshire (west of the Severn estuary)
- East–west (Variscan) — south of the Variscan front across the southern limits of the region, mainly the anticlinal Quantock–Cannington massif structure and the Creech Hill periclinal axis

Owing to considerable erosion of the Mesozoic and Permian younger cover rocks, the contribution of post-Jurassic movement to the various structural elements can only be inferred from studies in the adjoining Hampshire and Wealden regions.

A belt of north–south Malvernoid folding extends south across the region from the north, associated with the Malvern axis, to near the Variscan front in the south (Figure 30). This is the Bath axis and the fold belt contains the Coalpit Heath and Pensford–Radstock synclines (shown on Figure 25) and the May Hill–Huntley Anticline. Dips of between 10˚ east and 40˚ west are typically found on the west and east limbs of the folds respectively, with the Pensford–Radstock synclines being somewhat more symmetrical and open in geometry (Barton et al., 2002). The latter also extend south across the Variscan front. The Coalpit Heath Syncline is markedly asymmetrical, the eastern limb dipping west at about 40˚ and it appears to have developed as a result of buckling in association with the Variscan reactivation of older faults along the Malvern fault belt (Cave, 1977; Barron et al., 2011).

Aside from the north–south folds (Figure 30), immediately north of the Variscan front (Farmborough fault belt), folds associated with thrusts show two distinct trends (Figure 30). An east–west Variscan trend is represented by the Broadfield Down and Kingswood anticlines while, to the west of the River Severn, a belt of folding associated with the north-east to south-west lower Severn axis trend includes the Clevedon–Portishead (largely offshore) and Westbury anticlines, and the Avonmouth and Sand Bay–Nailsea synclines (Figure 25). The sinuous Westbury Anticline, reflecting both trends, is the principal structure above the Woodhill Bay–Ridgeway Thrust with Carboniferous rocks in the north-west limb steeply inclined (typically 70˚ north-west) and locally overturned and recumbent. Strata in the south-east limb typically dip at about 35˚ south-east and the two limbs are faulted together with little or no anticlinal closure. The Avonmouth Syncline is largely concealed beneath Quaternary deposits, but, on the sparse evidence available, it appears to be a more gently dipping, concentric fold (Barton et al., 2002).

The folds immediately south of the Variscan front occur as a series of generally east–west-trending, northerly verging structures with steepened northern limbs (Figure 30), associated with thrusts, including the Weston–Worle, Blackdown, Penhill, Beacon Hill, North Hill, Broadfield Down, Kingswood, Hamswell and Dulcote periclines and the Weston Bay Syncline . The Beacon Hill Pericline (Figure 29). lies in the south-east of the region and, traced eastwards, has a strongly curved nature, becoming north-east to south-west oriented, reflecting the orientation of later extensional faulting in the North Pewsey fault zone. The folding is associated with thrust displacement with the oldest and structurally uppermost thrust sheets containing the most tightly folded sequences. In the west of the region, exposed on the coast, are the Weston Bay Syncline and Weston–Worle Anticline, the latter associated with a southerly dipping thrust (the Worle Hill Thrust) in the crestal region (Whittaker and Green, 1983). The Mendip ridge comprises four *en échelon* periclines, of which the Blackdown Pericline (Figure 29) traceable over some 25 km (Green and Welch, 1965), underlain and generated by the Farmborough fault belt, is the westernmost. The fold is relatively simple but markedly asymmetrical, with a near-vertical or overturned northern limb and a southern limb inclined at 30˚ south (Barton et al., 2002). Structures above the Avon Thrust are typically more open and concentric in geometry, reflecting their association with smaller thrusts. The inclination of strata is generally 20 to 40˚ in the Broadfield Down Anticline, cut by a series of backthrusts (the Brockley and Yanley faults). An exception to these styles is the Kingswood Anticline, which is intensely folded and thrusted and represents an asymmetrical thrust culmination within which the mudstones formed a mechanically weak interval leading to disharmonic folding and many smaller thrusts (Barton et al., 2002).

To the west of the River Severn, in the area to the north of the Variscan front up to the Forest of Dean, the Palaeozoic rocks lie between two major anticlinal features of Malvernoid trend: the Usk Anticline (Wales region) and the Malvern axis, such that the area may be regarded broadly as a wrinkled syncline lying between these two anticlines (Welch and Trotter, 1961). A series of folds are developed that when traced from south to north, swinging from a north-west to a northerly direction (Figure 309). Respectively they include the Caerwant Syncline–Shirenewton Anticline–Mouton Syncline–Chepstow Anticline fold set (north-west to south-east); the Tiddenham Chase, Lydney, Howe Hill Main and Wigpool synclines; the Beachley Anticline, and the Staple Edge Monocline (north–south). North of these structures, the trend is again more north-west to south-east and includes the May Hill–Huntley and Woolhope anticlines. The folds are generally asymmetrical with the western limbs of the anticlines (or the eastern limbs of the synclines) highly inclined and facing west-south-west, reflecting the Malvern axis itself (Welch and Trotter, 1961). The folding is closely aligned to, but not entirely coincidental with, earlier intra-Carboniferous folding (Green, 1992).

The Staple Edge Monocline, developed on the eastern side of the Forest of Dean coal basin in the Mitcheldean area, is almost 5 km in length with a belt of nearly vertical beds producing a ‘downthrow’ to the west of more than 200 m (Welch and Trotter, 1961). The Woolhope Anticline, to the north of the Woolhope Fault, is defined by an inlier of early and middle Silurian rocks in the Ross-on-Wye district. It is mainly situated west of the Malvern lineament in the Welsh Borderland region, but extends into the region and is associated with a reverse fault (Chadwick and Evans, 2005). The fold is periclinal and asymmetrical, verging to the south-west, with the dip of the steeper south-west limb averaging 35˚to 40˚. It is formed by several discrete *en échelon* segments, segmentation appearing to be in part related to the presence of north-east-trending transverse structures, such as the Rock, Pentaloe and Woolhope–Cockshoots faults, just into the adjacent region, where lateral displacement on the cross faults vary considerably: up to 550 m on the Rock Fault and 150 m on the Woolhope–Cockshoots Fault (Welsh Borderlands region; Chadwick and Evans, 2005). The nature of the folds varies quite markedly along strike in the hanging-wall block.

The Quantock–Cannington massif is developed largely in the adjacent south-west England region, with only the eastern part impinging on the very south-west of the region. It is a broad Variscan anticlinal structure that formed a positive area during early Mesozoic times (Figure 30): essentially it is the western continuation of the footwall block to the Mere fault zone and the Creech Hill periclinal axis (the Bruton–Norton Ferris high; Holloway and Chadwick, 1984) in the adjacent Hampshire Basin region to the east. To the north lies the central Somerset basin (Whittaker and Green, 1983). This is a broad synclinal structure developed in the younger cover, the strike of which parallels that of the topographic trend of the Mendip Hills.

As alluded to previously, the level of erosion limits recognition of post-Variscan folding related to Cenozoic inversion. However, in the south-east of the region, the sinuous Creech Hill periclinal axis similarly represents a broad Variscan anticlinal structure or structural duplication, forming the core of the Bruton–Norton Ferris high (Holloway and Chadwick, 1984). This structure underpins an area of younger cover rocks to the north of the Mere fault zone and which suffered less subsidence during Mesozoic extension.

5.5 UNCERTAINTY

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

Across the region, acquisition of seismic reflection data is variable in extent, which thus provides varying levels of confidence in the identification, location and nature of major structures, particularly those concealed in the subsurface. Seismic reflection data have only been acquired over three small areas:

- the Jurassic Great Oolite Group crop in the north-east of the region, around Cheltenham, where coverage is good and these data have imaged well the structures associated with a major basin bounding fault system (Chadwick and Evans, 2005)
- the Mesozoic crop in the south-eastern extent of the region, across the Variscan front where coverage is less dense
- Palaeozoic (notably Silurian and Early Devonian) rocks to the west of the Bristol Channel–Severn estuary

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; 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. Elsewhere, reflection seismic data coverage is generally absent over the early Palaeozoic and coalfield crops, with faults being identified and located almost exclusively by surface mapping and coal mine records.

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 Bristol and Gloucester 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 BRISTOL AND GLOUCESTER REGION

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

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The GVS for the region (Table 3) divides rock units into three lithostratigraphical systems: Cambrian to Silurian basement rocks; older, Devonian to Carboniferous sedimentary rocks, and a younger sedimentary cover sequence of Permian to Cretaceous age. The regional groundwater flow systems in the Bristol and Gloucester region are conceptualised as being controlled by the broad distribution of these 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 constant head boundary imposed by the Bristol Channel.

The hydrogeology of the region can be conceptualised in terms of three geographical regions that broadly correspond to parts of the lithostratigraphical systems, as well as a single, deep groundwater system, as follows:

- a groundwater system within the younger sedimentary cover sequence under the the Cotswold Hills to the east of the region
- a groundwater system associated with the younger sedimentary cover sequence beneath the lowlands of the Severn valley and the Somerset Levels
- a groundwater system associated with the older sedimentary cover rocks beneath a central area, including the Mendip Hills and the Forest of Dean
- a groundwater system in the deep, relatively low-permeability basement rocks

6.3.1 Cotswold Hills

The Cotswold Hills, an area of high land to the east of the region, are underlain by a sequence of younger cover sediments that dip gently to the south-east, and the Cotswold escarpment is the surface-water divide of the Thames and River Severn catchments (Neumann et al., 1999). The Great and Inferior Oolite groups which crop out in this area form principal aquifers and receive direct recharge. Where overlain by low-permeability sedimentary rocks of the Kellaways and Oxford Clay formations, the Great and Inferior Oolite groups become confined. The groundwater potentiometric surface has a generally south-easterly dip (Neumann et al., 1999). A conceptual model of regional groundwater flow in the Cotswold Hills is shown in Figure 31. Groundwater flows north-west and south-east from either side of the groundwater divide. To the north-west it discharges via springs rising at the junction with Lias Group clays and to the south via springs controlled by hardgrounds, faults, or Lias Group mudstones exposed in deep valleys. Some groundwater recharges the confined aquifer to the south. Groundwater has relatively short residence times (Neumann et al., 1999). To the south, the sandstone aquifers are confined and recharge to the Great Oolite Group through younger, low-permeability deposits is minimal. There are small amounts of recharge through the Great Oolite Group to the Inferior Oolite Group. Here, residence times are relatively long with some groundwater recharging the deeper confined parts of the aquifer and some discharging via springs along river valleys or faults (Neumann et al., 1999). In the Malmesbury area, groundwater levels are up to 40 m higher in the Great Oolite Group than the Inferior Oolite Group due to the confining effects of the Lower Fuller’s Earth Member.

6.3.2 The Severn valley and the Somerset Levels

To the north-west of the Cotswolds and in the south-west of the region are areas of low-lying land: the Severn valley and the Somerset Levels. These are typically underlain by a sequence of low-permeability rocks from the younger sedimentary cover sequence that are slightly older than those in the Cotswolds, including the Lias Group and Mercia Mudstone Group rocks, and more permeable Permo-Triassic sandstones, although the latter are not currently exploited as an aquifer. Aquifers in this area are commonly confined by low-permeability Lias Group and Mercia Mudstone Group rocks, particularly in the centre of the basins. Regional groundwater flow in the Worcester basin is controlled by piezometric levels in the high ground to the west, north and east. Direct recharge of the Permo-Triassic sandstones occurs in the west and north of the basin, and indirect recharge occurs by downward vertical flow below the high ground of the Cotswolds. Most water entering the Permo-Triassic sandstone in the outcrop area is discharged to local river systems, but some flows into the confined aquifer.

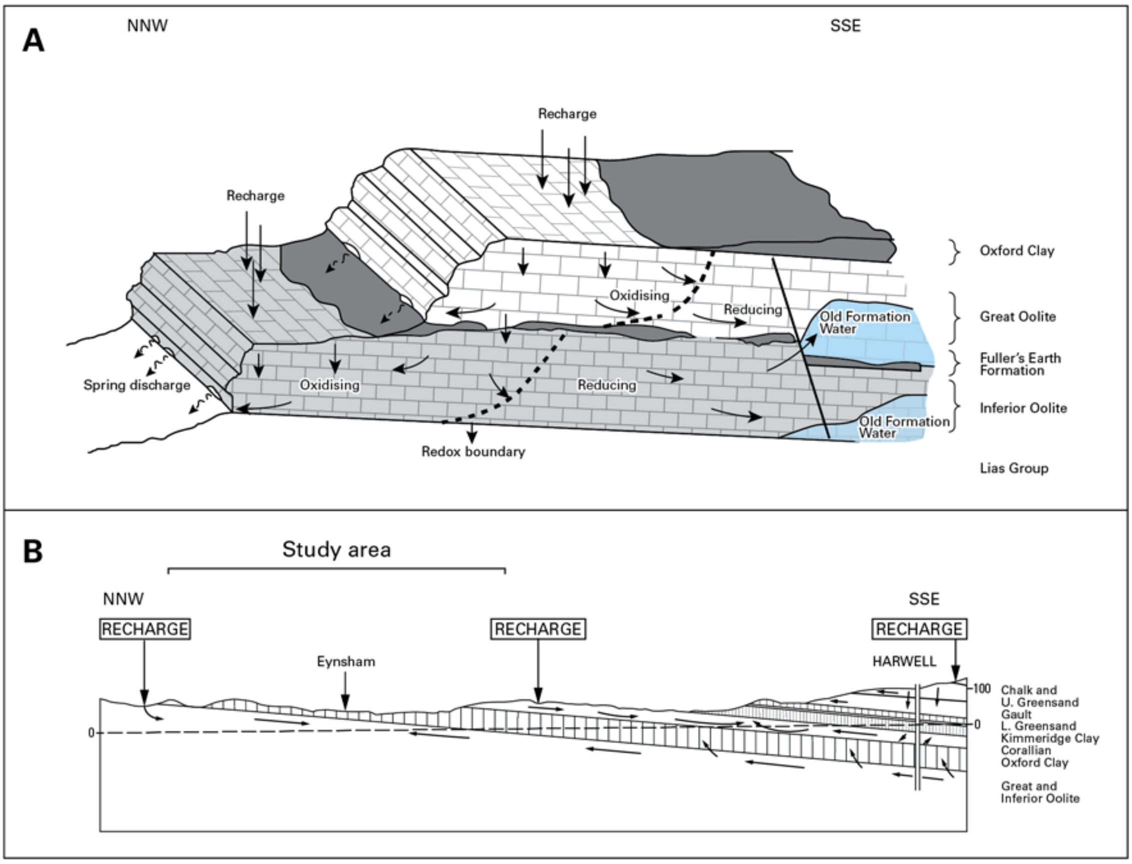


Figure 31 Conceptual model of regional groundwater flow in the Cotswold Hills, after Neumann et al., 1999. A) Conceptual model of the groundwater regime in the Cotswolds study area; B) Groundwater movement in the study area is towards the south-south-east. British Geological Survey © UKRI 2018

6.3.3 Central area

The central area is underlain by a structurally complex sequence of Palaeozoic and Mesozoic rocks. In this area limestones of the Carboniferous Limestone Supergroup dominate the hydrogeology. There is extensive karst in the limestones in this area, which can result in highly focused and rapid groundwater flow, making it difficult to characterise the subregional hydrogeology. Generally in this area, flow is towards the centre of the basin from surrounding higher ground. The thermal springs of Bath and Bristol also occur in this area, which are inferred to have been fed by groundwater rising from up to 3 km depth through the Carboniferous limestones. In the Mendip Hills, springs rise in the (mainly) Devonian cores, infiltrate into the Carboniferous limestone, and flow through the rock to form springs at the periphery of the hills. These predominantly occur where the Carboniferous limestone dips beneath the Triassic mudstones (Allen et al., 1997). The Mercia Mudstone Group marginal facies is in hydraulic continuity with the Carboniferous Limestone Supergroup or, less commonly, the Upper Old Red Sandstone Group. Differences in head can be in either direction and in some places Triassic groundwater is lost rapidly to the Carboniferous limestones. Artesian flow due to confinement by overlying mudstones is often encountered (Jones et al., 2000) particularly in the area of the Mendip Hills.

Note that Devonian rocks (Upper Old Red Sandstone Group), primarily to the west of the River Severn, are aquifers of local importance (Moreau et al., 2004). The Devonian sandstone comprises a series of interbedded sandstones, siltstones and mudstones (Moreau et al., 2004). These rocks also form much of the subsurface in the east, but at greater depth where little is known about them. In the Wye valley the unit is bound to the south and east by Carboniferous or younger rocks, and, to the north, older rocks (Ordovician and Silurian) (Moreau et al., 2004). The unit crops out as inliers surrounded by limestones of the Carboniferous Limestone Supergroup on the Mendip Hills, underlying these elsewhere. As these rocks are not designated as a principal aquifer they are not considered further here.

Deep groundwater system

There is no hydrogeological information in the literature reviewed on the basement rocks of the region. By analogy with similar lithologies in other regions at similar depth intervals, the permeability of this groundwater system is inferred to be low, however, no information is available on hydraulic boundary conditions, the relationship with the overlying groundwater systems, the distribution of heads, or regional flow patterns in this groundwater system.

Groundwater flow from depth and between groundwater systems

Rocks from the sedimentary cover sequences are found in the depth interval of interest across the region. There is a range of pathways (both known and potential) for groundwater movement from the depth range of interest to the surface, principally associated with regional-scale structures and with anthropogenic features (e.g. boreholes and mines) and between groundwater systems. These potential pathways for groundwater movement from depth and between groundwater systems are discussed after a description of each of the three groundwater systems.

6.3.4 Hydrogeology of the younger sedimentary cover sequence to the east of the region

The following is a description of the hydrogeology of the younger sedimentary cover sequence to the east of the region from the Chalk Group to the Inferior Oolite Group. It primarily describes units that are hydrogeologically important in the Cotswolds in the east of the region.

6.3.4.1 CHALK AND CORALLIAN GROUPS

The Chalk Group and the Upper Greensand Formation are present only in the south-east of the region at depths of less than 20 m and so, although they are principal aquifers in other regions, are not described here. Similarly, the Gault and Kimmeridge Clay formations only have very limited extent within the region and are only present at very shallow depths, so they too are not described here.

The Corallian Group is a principal aquifer in other regions, but is only present very locally in this region and not at any depth, so it too is not described here.

6.3.4.2 KELLAWAYS AND OXFORD CLAY FORMATIONS

There is limited information about the hydraulic properties of these formations in this area, and no information from >200 m depth in the literature reviewed. In the south around Wincanton, they act as aquicludes below the Corallian Group aquifer (Bristow et al., 1999). Locally, small quantities of water can be obtained from the upper, weathered, part of the unit, although the water quality is likely to be poor and is often ferruginous (Bristow et al., 1999).

6.3.4.3 GREAT OOLITE GROUP

The Great Oolite Group consists of calcareous mudstone-dominated and ooidal, bioclastic and fine-grained limestone (BGS, 2016) within which a number of units are identified as aquifers: the Chalfield Limestone, Tresham Rock, Athelstan Oolite, Chipping Norton Limestone, Taynton Limestone, Hampen, White Limestone, Forest Marble, Corsham Limestone and Cornbrash formations.

South of Wellow, the Great Oolite Group comprises predominantly mudstone. There is very limited information about the hydraulic properties of this mudstone unit within the Great Oolite Group in the region, and no information from > 200 m depth in the literature reviewed, although in the south around Wincanton, it has been characterised as behaving as an aquiclude (Bristow et al., 1999).

Elsewhere, the ooidal, bioclastic and fine-grained limestones of the Great Oolite Group are considered a principal aquifer and are extensively used for water supply in the Cotswold Hills (Barton et al., 2002). However, the Fuller’s Earth Formation, Frome Clay Formation and clays of the Forest Marble Formation are generally considered aquicludes (Bristow et al., 1999). In the south-west of the area the Fuller’s Earth Formation is a significant clay layer that hydraulically separates the Great and Inferior Oolite, with limited groundwater movement between the two aquifers via faults.

The Great Oolite Group has relatively low intrinsic intergranular permeability since it is normally well cemented and massive, and groundwater flow is predominantly through fractured horizons. Tracing in the By Brook tributary of the River Avon (east of Bath) indicated rapid fracture flow, with velocities of 10 000 m/day. Changes in water quality are seen as the aquifer becomes confined to the east (Figure 31). A hydrochemical boundary marks a change from typical unconfined Ca-HCO_3-type groundwater to confined Na-HCO_3-type groundwater (Morgan-Jones and Eggboro, 1981: Allen et al., 1997; Neumann et al., 1999). In the Great Oolite Group this boundary was 1 to 2 km downdip from the edge of the confined aquifer in the mid-1970s, and 2 km downdip in 1992 (Allen et al., 1997). Tritium concentrations measured in the 1970s indicate that, close to the recharge area, a large proportion of groundwater has been derived from recent (post-1953) rainfall (Morgan-Jones and Eggboro, 1981) (Neumann et al., 1999). However, the proportion of recent groundwater in the confined aquifer is not clear, with some studies noting that all groundwaters, including some from the confined zone, have some recent water and others finding no significant contribution from modern water > 3 km from outcrop (Neumann et al., 1999).

6.3.4.4 Inferior Oolite Group

The Inferior Oolite Group is a varied succession of ooidal, peloidal, sandy, ferruginous and shelly limestones with subordinate sandstone, lime mudstone and mudstone beds (BGS, 2016), within which a number of linestone units are identified as aquifers: the Birdlip Limestone, Aston Limestone and Salperton Limestone formations.

In the Cotswold Hills, as well as being in hydraulic connection with the Great Oolite Group where the Fuller's Earth Formation is thin, the Inferior Oolite Group can also be in hydraulic continuity with the Bridport Sand Formation of the Lias Group in the south (Allen et al., 1997). At Oldford near Frome, the Inferior Oolite Group aquifer is recharged from the Carboniferous Limestone Supergroup with which it is in hydraulic continuity 1.5 km away, despite the two formations being separated by 33 m of Lias Group clays at this site (Allen et al., 1997).

Hydrogeological properties of the Inferior Oolite Group are similar to the Great Oolite Group. It has low intergranular permeability and groundwater flow is predominantly along preferential flowpaths such as fissures, faults and fracture zones (Neumann et al., 1999). Fractures can be present at depth: for example, at the Meysey Hampton Borehole (south of Cirencester) fractures were encountered at 116, 122, 130 and 131 to 131.8 m and 80 to 90 per cent of the flow originated from 130 to 132 m depth and artesian flow increased significantly with depth of drilling. In a nearby observation borehole, fractures were visible at 102.5, 105 and 122 m bgl. This unit tends to be more fractured than the Great Oolite Group because it has a lower clay content (Allen et al., 1997). In the Inferior Oolite Group the hydrochemical boundary (from typically Ca-HCO_3-type unconfined water to Na-HCO_3-type confined water) was found at 4 to 8 km downdip of outcrop in the late 1970s and at 7 to 8 km in 1986 (Allen et al., 1997). The transition is conceptualised as being due to groundwater discharge down dip rather than the influx of Great Oolite Group groundwater.

6.3.5 Younger sedimentary cover in low-lying areas west of the Cotswolds

The following is a description of the hydrogeology of the younger sedimentary cover sequence from the Lias Group to the Permian Bridgnorth Sandstone Formation. It primarily, although not exclusively, describes units that are hydrogeologically important in the relatively low-lying areas to the west of the Cotswolds, such as the Severn valley and Somerset Levels areas of the region.

6.3.5.1 Lias Group

The Lias Group consists of mudstones, siltstones, limestones and sandstones. There is very limited information about the hydraulic properties of the lower permeability units in the area at > 200 m depth. However, the Bridport Sand Formation and Blue Lias Formation (marginal facies) of the Lias Group are designated as principal aquifers.

There is no hydrogeological information for the Bridport Sand Formation at depths > 200 m in the literature reviewed. Flow of groundwater < 200 m is thought to be largely intergranular, but there is some evidence that fracture/fissure flow is important (Shand et al., 2004).

There is little information about the hydraulic properties of the Blue Lias Formation (marginal facies) in the region. Where the unit directly overlies the Carboniferous Limestone Supergroup there is hydraulic continuity and water passes down into the underlying rocks (Jones et al., 2000). The unit is separated from Carboniferous limestone where the Penarth Group mudstones intervene and a perched water table may occur within the unit. However, in places there can still be hydraulic connection where the Penarth Group is present. Shafts and adits at Shepton Mallet failed to obtain any water from the Blue Lias Formation (marginal facies) (Jones et al., 2000).

In the Severn valley and Somerset Levels area and the Cotswold Hills, the limestones and mudstones which make up the Lias Group are typically poorly permeable (Green and Welch, 1965; Whittaker and Green, 1983) and are therefore poor aquifers (Barron et al., 2002). Groundwater predominantly flows through fractures (Whittaker and Green, 1983).

6.3.5.2 Mercia Mudstone Group (marginal facies)

The Mercia Mudstone Group consists of mudstones and subordinate layers of sandstones. There is little information on hydrogeological properties at > 200 m in the reviewed literature. Although around the Mendip Hills the Mercia Mudstone Group (marginal facies) is a principal aquifer, in the central area the mudstones are considered to be low permeability and generally non aquifers (Jones et al., 2000). The mudstones effectively confine the Sherwood Sandstone Group aquifer and the Carboniferous Limestone Supergroup aquifer systems where overlying them (Jones et al., 2000; Environment Agency, 2004). However, sandstone layers or 'skerries' up to 7 m thick in the Mercia Mudstone Group form local aquifers (BGS, 2016).

In the Severn valley and Somerset Levels the Mercia Mudstone Group is generally considered an aquiclude (Downing and Gray, 1986) due to the low-permeability mudstones (Barclay et al., 1997). However, it is the most important source of water in terms of the total number of licensed abstractions and geographical distribution in some parts, such as Worcestershire (Jones et al., 2000) where the Arden Sandstone Formation is present. Other local aquifers can be formed by dolomitic siltstone and sandstone, or skerries, within the group, particularly from where fissures are present (Barclay et al., 1997). The unit in this area is disturbed by numerous small faults, which can isolate blocks of local aquifers (Hobbs et al., 2002). Groundwater quality is generally good, although very hard, often exceeding 500 mg/l (of $CaCO_3$). Brine was obtained from the 1105 m-deep Puriton Borehole (near Bridgwater) in the Mercia Mudstone Group (to 388 m bgl) and Sherwood Sandstone Group (to 1105 m depth) and is likely to be found in certain other parts of the district, particularly near the margins of the central Somerset basin where Triassic salt-bearing horizons approach the surface (Whittaker and Green, 1983). There is no hydrogeological information in the literature reviewed for the Mercia Mudstone Group in the area of the Cotswold Hills.

6.3.5.3 Sherwood Sandstone Group and Permian Bridgnorth Sandstone Formation

There is no hydrogeological information about these units in the Cotswold Hills and central area in the literature reviewed. In the Severn valley and Somerset Levels the units are often considered as part of a Permo-Triassic succession of aquifers comprising a series of local sandstone aquifers separated by argillaceous beds (Downing and Gray, 1986). There is very little information in the literature reviewed on these units in this area in the depth range of interest. Although more mineralised than at outcrop, waters in some confined boreholes (like Upton upon Severn) are adequate for public water supply (Barclay et al., 1997). Oxygen isotope analyses from an interval from 936 to 942 m depth in the Wildmoor Sandstone Member at the Kempsey Borehole show groundwater is similar to present day and suggests a substantially young (Quaternary) groundwater (Darling et al., 1997). Combined with the relatively low salinity, this indicates that the aquifer system has been considerably flushed by meteoric water, possibly by recharge of groundwater moving down through the overlying Mercia Mudstone Group (Downing and Gray, 1986).

6.3.6 Older sedimentary cover sequence

The following is a description of the older sedimentary cover sequence from the Carboniferous to the Devonian. This cover sequence primarily, although not exclusively, crops out in relatively high land in the central areas of the region, e.g. the Mendip Hills and the Forest of Dean.

6.3.6.1 Warwickshire Group

The Warwickshire Group consists of mudstones, siltstones, sandstones, coals, ironstones and ferricretes. There is no hydrogeological information about the Warwickshire Group in the region in the depth range of interest in the literature reviewed.

6.3.6.2 CARBONIFEROUS LIMESTONE SUPERGROUP

The Carboniferous Limestone Supergroup unit is comprised of the Pembroke Limestone and Avon groups, with subordinate sandstones and argillaceous rocks. A number of units within the Pembroke Limestone Group are classified as aquifers: the Oxwich Head Limestone, Clifton Down Mudstone, Burrington Oolite, Vallis Limestone, Gully Oolite, Goblin Combe Oolite and Cromhall Sandstone formations, and the Black Rock Limestone and Hunts Bay Oolite subgroups.

There is no information on the hydrogeological properties of Carboniferous Limestone Supergroup unit in the Severn valley and Somerset Levels areas in the literature reviewed, however, there have been a number of hydrological studies of the unit in the central area.

In the central area, the unit is in hydraulic continuity with the Mercia Mudstone Group (marginal facies) where present, and confined above by the Mercia Mudstone Group and Westphalian-aged rocks. Where the Blue Lias Formation directly overlies the limestones of the Carboniferous Limestone Supergroup there is hydraulic continuity. Where the Penarth Group intervenes, the mudstones may confine the Carboniferous limestone. The Avon Group unit at the base of the Pembroke Limestone Group is the lower limit of the aquifer (Environment Agency, 2004) and this rests conformably on sandstones of the Upper Old Red Sandstone Group (Jones et al., 2000).

The unit is typically indurated and fracture flow controls the permeability (Downing and Gray, 1986). In the Bath–Bristol area, permeability has been enhanced by the effects of folding, faulting and jointing (Downing and Gray, 1986). Around the Mendip Hills the limestones of the Carboniferous Limestone Supergroup are highly karstic and the most important aquifer in the Bristol area (Allen et al., 1997). The aquifer provides significant groundwater from major springs (Allen et al., 1997) particularly at the foot of the Mendip Hills, however, good yields from boreholes depend on encountering large fissures and the extent of their connection. Flow velocities within the major conduits are very rapid (up to 21 km/day) (Environment Agency, 2004). Bedding and tectonic structure have been shown to have an influence on the conduit network, with flow down steeply dipping bedding and cutting across to others through joints 40 to 50 m below the present-day water level (phreatic looping) (Allen et al., 1997). Drilling in quarries has proved karstic voids at greater depth but it is not known if they form part of a present-day, active flow or drainage network (Allen et al., 1997). Limestones of the Carboniferous Limestone Supergroup can behave as a multilayered aquifer with the limestones and arenaceous horizons acting as aquifers, and argillaceous horizons (or well cemented limestones) as aquicludes or aquitards (Jones et al., 2000).

Thermal springs at Bath and Hotwells rise through the Carboniferous Limestone Supergroup and are described in the section on connections between groundwater systems.

6.3.6.3 DEVONIAN ROCKS

Units within the sequence of Devonian sedimentary rocks of the region may be considered as local aquifers with fracture flow typically controlling permeability (Environment Agency, 2004). Information on their hydrogeological characteristics above the depth interval of interest can be found in Allen et al. (1997), Jones et al. (2000) and Moreau et al. (2004), however, as none of these rocks are designated as a principal aquifer in the region they are not considered further here.

6.3.7 Hydrogeology of the basement rocks

6.3.7.1 SILURIAN TO DEVONIAN BASEMENT ROCKS

In some places, extrusive igneous basement rocks are considered a local aquifer with fracture flow (Environment Agency, 2004), and the Silurian andesites of Beacon Hill have been documented as being hydraulically connected to the Late Devonian Portishead Formation by faults and fractures, which result in locally high permeabilities . Other that this there is no further hydrogeological information on these units in the literature reviewed.

6.4 EVIDENCE FOR CONNECTIONS BETWEEN GROUNDWATER SYSTEMS

6.4.1 Separation

Central area: While exposed at the surface in the Mendip Hills, and around the Forest of Dean, the water-bearing rocks of the Carboniferous limestone in the centre of the Bristol–Bath area are hydraulically separated from the surface by up to 700 m of low-permeability Lias Group (in places), Mercia Mudstone Group and Westphalian-aged rocks. Adjacent to the Mendip Hills the Mercia Mudstone Group (marginal facies) is permeable and therefore does not act to confine the limestone.

Severn valley and Somerset Levels: In the Worcester and Somerset basins, permeable Permo-Triassic sediments are separated from the surface by 200 to 1000 m of low-permeability Lias Group and Mercia Mudstone Group rocks. Carboniferous limestones underlie these units in the Somerset basin, and Silurian rocks in the Worcester basin. However, it is not known if they are in hydraulic continuity. The Kempsey Borehole in the Worcester basin showed differences in groundwater chemistry between the Permian Bridgnorth Formation and the Triassic Wildmoor Sandstone Member, suggesting that, despite both being permeable formations, flow is restricted between the two formations (Downing and Gray, 1986).

Cotswold Hills: The Great and Inferior Oolite group aquifer systems in the Cotswold Hills are in direct contact with the surface. They are underlain by up to 800 m of low-permeability Lias Group and Mercia Mudstone Group rocks, which hydraulically separate them from the deeper Sherwood Sandstone Group and the limestones of the Carboniferous Limestone Supergroup.

6.4.2 Geological pathways

6.4.2.1 THERMAL SPRINGS

There are thermal springs in Bath and Bristol and their locations are shown on Figure 38. The Bath hot springs are the hottest in the UK. Under natural heads these springs rise through the Carboniferous Limestone Supergroup and the Charmouth Mudstone Formation (Lias Group) emerging 50 m above the top of the Carboniferous Limestone Supergroup in river terrace gravels of the River Avon (Barron et al., 2011). Carboniferous limestone adjacent to the hot springs was found to be heavily karstified (Barron et al., 2011). The combined flow is around 15 l/s (Barron et al., 2011). King’s Spring yields 13 l/s at a constant 46.5ºC (within 0.5 ºC since 1754) (Andrews et al., 1982). Hetling (Hot Bath) Spring issues at 48ºC and Cross Bath 41 to 42ºC (Downing and Gray, 1986).

However, stable isotopes ($\delta^{18}O$ -7.4 and $\delta^{2}H$ -47.0 ‰) suggest a meteoric origin for the springs, recharged in similar climatic conditions to today, and ratios of dissolved atmospheric inert gases in the thermal waters indicate recharge temps of 9ºC (Andrews et al., 1982). The concentration of dissolved Si (SiO_2), of 44.1 mg/l (Downing and Gray, 1986) indicates a maximum groundwater temperature of 69 to 99ºC, and a corresponding likely maximum circulation depth of 3 km, in line with recent geological models. This would suggest that the return to the surface is through a sufficiently indirect route in order to cool the groundwater by about 20ºC (Edmunds et al., 2014). The maximum age based on ^{14}C is thought to be around 20 000 years (Downing and Gray, 1986). Since recharge temperatures of 9ºC are not likely in the Pleistocene, a mean residence time of < 12 000 years is more probable (Edmunds et al., 2014). For a likely residence time of 1 to 12 000, years a large storage volume and circulation pathway is required, therefore, with typical porosities, much of the Bristol–Bath basin must be involved in the storage of the thermal waters (Edmunds et al., 2014). A possible model of the geological situation at the Bath springs (the Mendip model) is shown in Figure 32. Recharge in the Mendip Hills (15 km to the south-west) has been inferred, which would provide sufficient elevation to control flow across the basin (Andrews et al., 1982; Downing and Gray, 1986), with a travel time of 3000 (Andrews et al., 1982) or 4000 years (Andrews, 1991). While traditionally the Mendip Hills were considered the recharge location, it is now thought that recharge could occur anywhere where the limestones occur around the basin rim (Edmunds et al., 2014). The hydraulic connection with depth is thought to be provided through a fault zone.

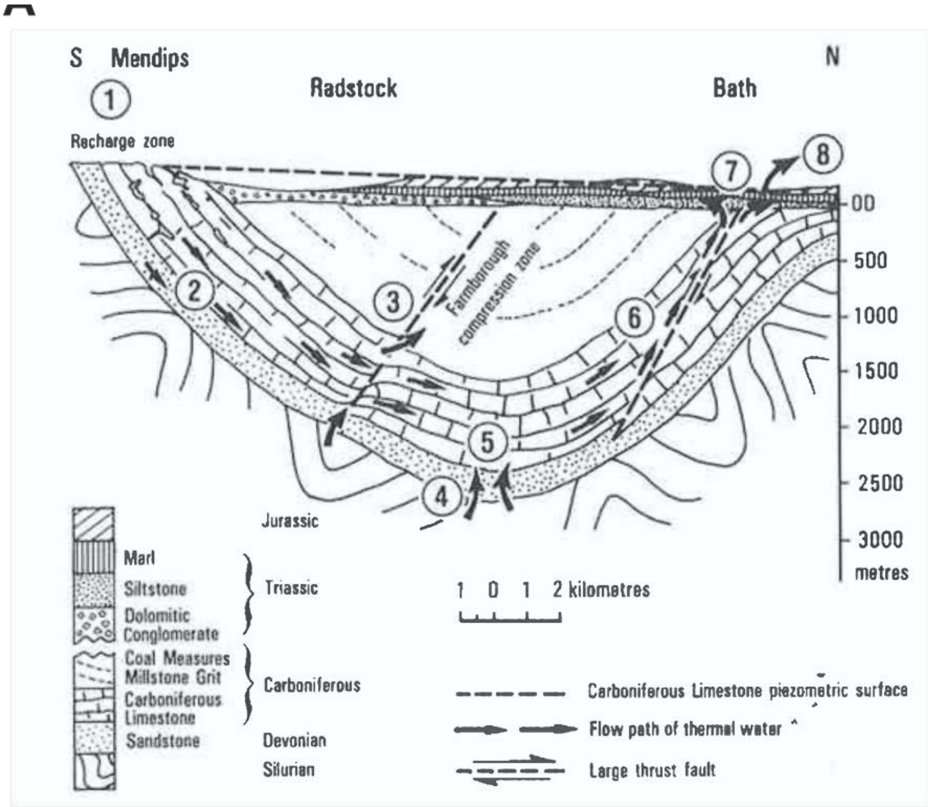


Figure 32 Conceptual model of the flow path of thermal water in the Bath–Bristol area. 1) recharge (9–10ºC) at the Carboniferous Limestone Supergroup/Upper and Lower Old Red Sandstone groups outcrop; 2) downdip and down-gradient flow, assisted by karstic features; 3) possible gain from early Palaeozoic and leakage to late Carboniferous via Farmborough compression zone; 4) some leakage of very old ^{4}He-bearing groundwater from Old Red Sandstone Group and possibly early Palaeozoic; 5) storage and chemical equilibration within the Carboniferous Limestone Supergroup, at 64–96ºC; 6) relatively rapid ascent along thrust fault system; 7) some recharge of Triassic by thermal water at Bath; 8) discharge of the thermal springs at Bath (46.5ºC).

Bristol has five thermal springs (Barton et al., 2002). Hotwells Spring (Figure 38), 200 m south of the Clifton Suspension Bridge, at 2 m above OD, issues at 0.2 l/s at 24ºC (Andrews et al., 1982), and is a mixture of Bath-type thermal water and shallow, Carboniferous limestone water in the ratio of 1:2.3 (TDS 1090 to 1110 mg/l, Cl 80 to 79 mg/l (Hawkins and Kellaway, 1991; Andrews et al., 1982). It emerges at the lowest available point in the aquifer and is thought to be fed by 4000 m-deep groundwater, rising along a fracture belt in the Carboniferous limestone (Hawkins and Kellaway, 1991). St Vincent's spring (Figure 38) also emerges from the Carboniferous limestone, the temperature has been measured as 15.8 and 20ºC (Stanton, 2005 and Richardson, 1930 respectively). The water flowed at about 1.5 l/s when measured on 22/10/1992. The springs at higher elevations are also warmer than groundwater, but are diluted by cold water from above, and issue at only 13.8ºC (Barton et al., 2002). An easterly or northerly origin for these springs, rather than a direct connection with the Mendip Hills, was suggested by Kellaway (1991). However, the Mendip–Avon fracture zone model proposed by McCann et al. (2013) suggests a common origin for the Bath and Bristol springs, thus with an origin also in the Mendip Hills, rising along the fracture zone along the Avon river. It is thought likely that concealed thermal waters could emerge elsewhere in the Avon valley (Downing and Gray, 1986).'

6.4.2.2 Structure

Although the region is structurally complex (Section 5), these is no systematic evidence across the region for the role of folding or faulting in modifying the regional hydrogeology. As described above, faulting has been inferred to be involved in the relatively rapid movement of hot water from depth to the Bath springs (Figure

32). However, in the central area aquifers are compartmentalised by faulting (leading to rapid decline in borehole yields) but the effects of folding are complex and difficult to predict (Jones et al., 2000). In the Cotswold Hills faults with throws of 30 to 50 m are known to occur in the younger sedimentary rocks, in the Inferior Oolite and Great Oolite groups (Allen et al., 1997), so that locally the two groups can be laterally hydraulically connected (Allen et al., 1997).

6.4.2.3 KARST

Central area

Karst is extensively developed in the limestones of the Carboniferous Limestone Supergroup where it is exposed or near the land surface, for example in the Mendip Hills (Waltham et al., 1997). The central part of the Mendip Hills, around Cheddar Gorge and Priddy, is the highest part of the plateau and the most well-developed karst is found here. Streams sinking at the margins of the Devonian sandstone outcrop emerge on the flanks of the limestone outcrop. These flow through well-connected, integrated karstic conduits, often with distinctive phreatic loops (Waltham et al., 1997) that can reach depths of about 90 m, more than 30 m below sea level (Waltham et al.,1997). Examples of karstic cave systems include:

- Gough’s Cave, with Great Oone’s Hole and Long Hole having more than 2200 m of explored passages, over a total vertical range of 180 m (Waltham et al., 1997)
- GB Cavern and Charterhouse Cave, a 7 km-long cave system reaching a depth of 228 m, which extends south almost to Cheddar Gorge
- Longwood Swallet, comprising over 1600 m of cave passages, reaching to a depth of 175 m
- Upper Flood Swallet at Charterhouse, a 4 km-long cave system draining south-east, reaching a depth of 129 m

The Priddy Caves are a suite of swallet cave systems underlying the limestone plateau on south and south-west slopes of North Hill, around Priddy. The water emerges at Wookey Hole, a large resurgence cave on the south margin of the Mendip limestone plateau passing from Carboniferous limestone into a cemented scree of limestone debris (Mercia Mudstone Group (marginal facies)).

6.4.3 Anthropogenic pathways

There are a number of boreholes > 200 m deep in this area, particularly towards the eastern end of the Mendip Hills and around Bristol, but there is no evidence in the literature reviewed that they act to connect deep and shallow groundwater systems.

There are coalfields with a legacy of abandoned mines up to 300 m deep across the region (Section 8). Coal mines of less than 100 m below the NGS datum are present north of the Mendip Hills to north of Bristol and around the Forest of Dean. Under natural conditions, Westphalian-aged rocks act as individual aquifers separated by intervening low-permeability, argillaceous horizons constituting a complex multi-layered aquifer system. However, these hydraulic relationships have been disrupted by mining subsidence, which has created hydraulic continuity between water-bearing layers and in some locations between aquifer horizons and mine workings (Jones et al., 2000). Water levels in the Forest of Dean area were lowered during the 18th century, initially by adits and subsequently by pumping. When mining ceased, the deeper levels flooded but many drainage adits continue to function (Aldous et al., 1986; Jones et al., 2000). Aldous et al. (1986) has detailed the problems of management of the active groundwater system associated with the abandonment of coal mines in the Forest of Dean, including deep and shallow barrier removal, post-abandonment collapse and waste disposal.

Carboniferous limestone quarries for aggregate in the eastern Mendip Hills are excavated below the water table and pump out large quantities of water, which significantly affect groundwater flow patterns up to several kilometres away (Environment Agency, 2004).

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

It is clear from the recent geological record that glaciers have been repeatedly active within the UK landscape over the past two and half million years (Clark et al., 2004; Lee et al., 2011). Numerous periods of glaciation have been recognised, although the scale and extent of glaciers have varied considerably. Most glaciations have been comparatively small (i.e. highland glaciations), although some have been more extensive with glaciers expanding into lowland parts of the UK, i.e. lowland glaciations (Clark et al., 2004; Lee et al., 2011). Over the past half a million years, at least two continental-scale glaciations have affected the UK with ice sheets covering parts of lowland UK, on one occasion as far south as the London area (Figure 33; 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

The westernmost parts of the Bristol and Gloucester region are situated within the limits of continental glaciation during the last two and half million years (Quaternary Period; Figure 33; Shaw et al., 2012; Clark et al., 2004). Based upon the absence of evidence for past glaciations of lowland scale in the recent geological past, the region may only experience continental-scale glaciation infrequently over the next million years (RWM, 2016b). This may, over multiple episodes of glaciation, result in localised meltwater erosion to depths that reach the very top of the depth range of interest. Glaciation of the region and adjacent onshore areas (e.g. Wales and central England) may lead to the region being affected by isostatic rebound and/or a glacier forebulge (RWM, 2016b). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (RWM, 2016b). Coastal areas of the Bristol and Gloucester region may be susceptible to saline groundwater incursion due either to global sea-level change (driven by global patterns of glaciation) or regional isostasy (RWM, 2016b). Saline groundwater incursion may alter the temporal and spatial patterns of groundwater behaviour (RWM, 2016b).

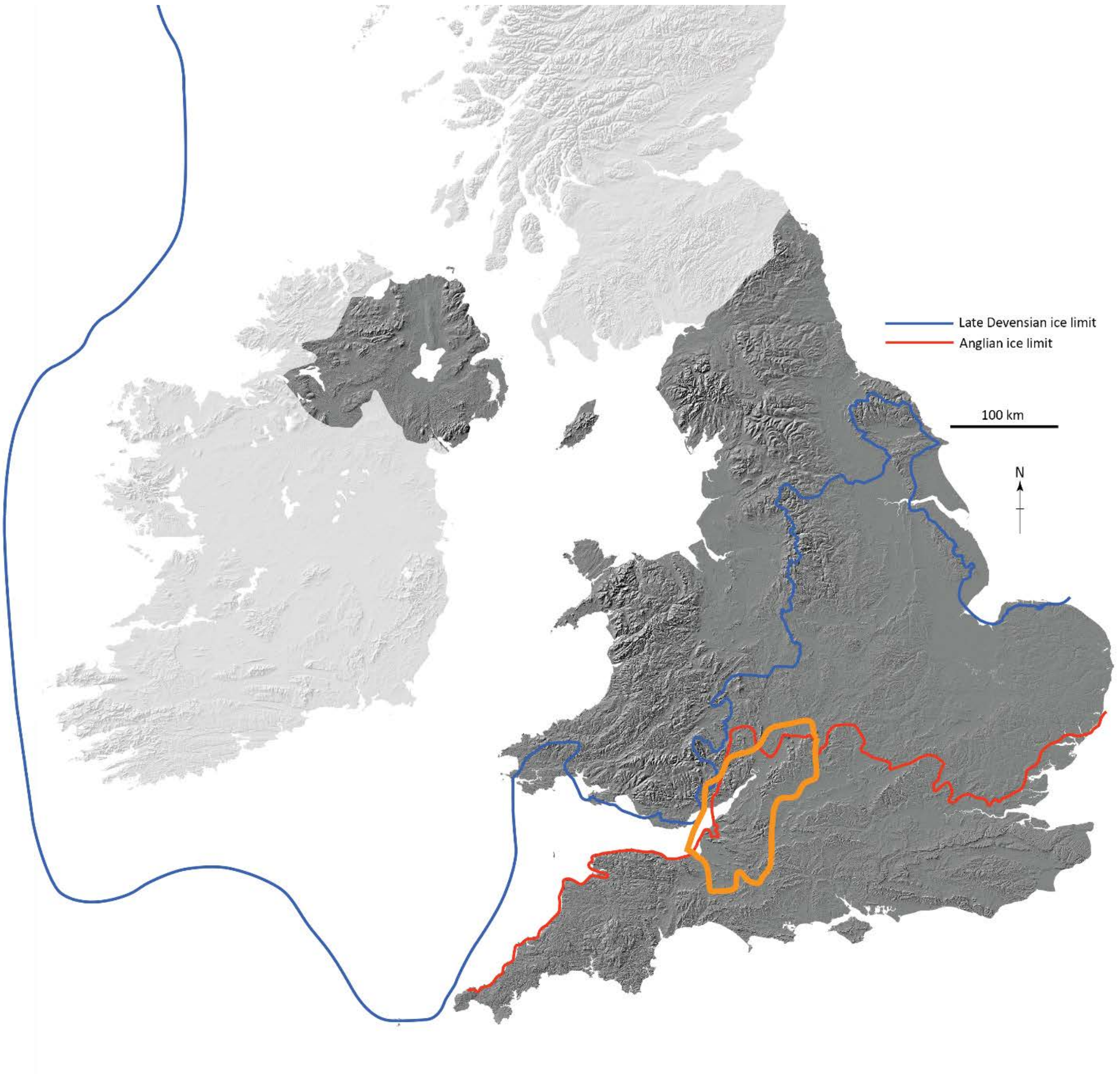


Figure 33 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and late Devensian (around 30 to 16 ka). The location of the Bristol and Gloucester region is delineated by the orange line. Produced using Copernicus 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 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 Bristol and Gloucester 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, RWM, 2016b). The development of permafrost can affect groundwater chemistry and behaviour and, in combination with possible localised glacial erosion, future development of permafrost may be to several hundred metres beneath the current ground surface.

7.4 SEISMICITY

7.4.1 A UK-scale context

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

Earthquake activity is greatest at the boundaries between the Earth's tectonic plates, where the differential movement of the plates results in repeated accumulation and release of strain (Figure 34). 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 34). 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).

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).

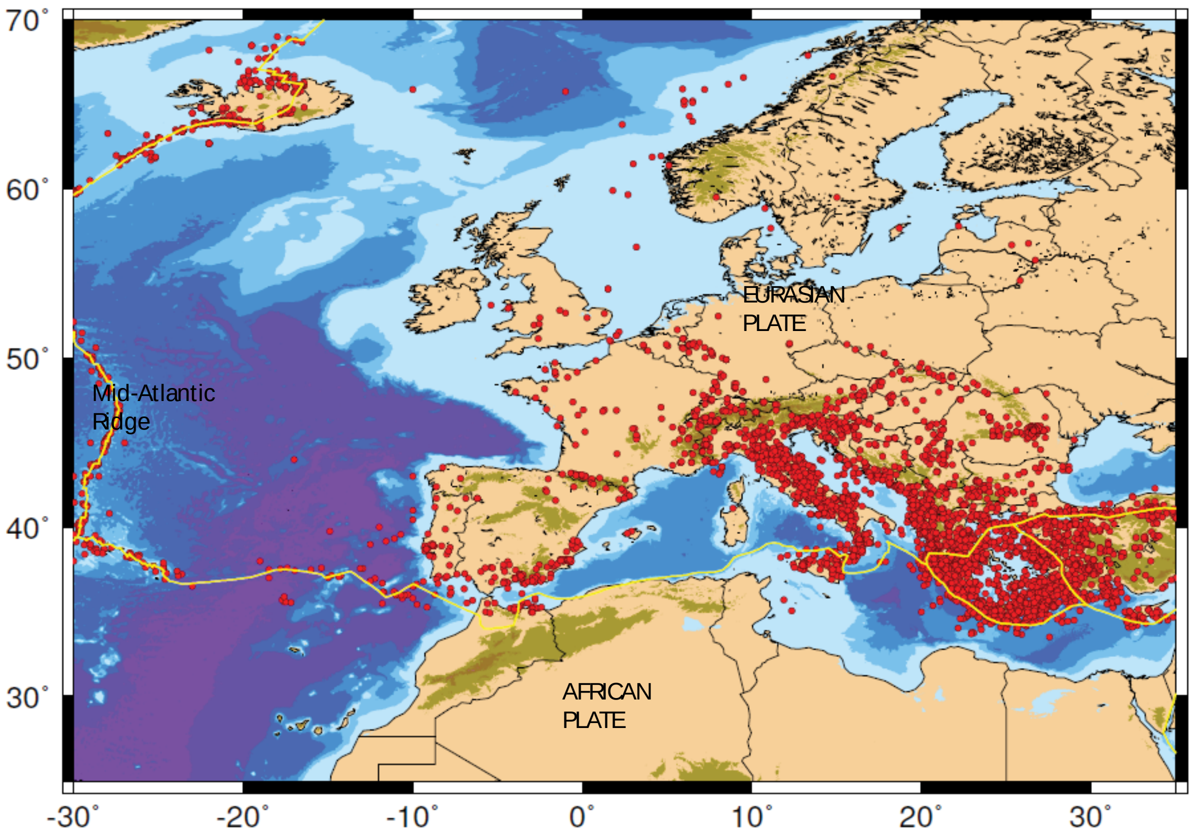


Figure 34 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

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 3. The catalogue for earthquakes of Mw 3 and above is complete from 1970, i.e. the beginning of the instrumental monitoring of the British earthquakes. The catalogue is complete for earthquakes above Mw 4 and Mw 5 from 1750 and 1650, respectively. In south-east England, the catalogue extends further back in time (to the 14th century) for earthquakes of Mw 5.5 and above.

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

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

Figure 35 shows a map of all of the main shocks in the catalogue. The symbols are scaled by magnitude (Mw). It is worth noting that the location uncertainty is ±5 km for instrumental earthquakes and up to ±30 km for historical earthquakes (Musson, 1994). An analysis of the British seismicity clearly shows that it is not correlated with the major tectonic structures that bound the tectonic terranes in the UK (Musson, 2007). The terranes are homogeneous in terms of crustal properties (e.g. distribution and style of faulting), but the seismicity within each block is heterogeneous (Musson, 2007). There are spatial variations in the level of seismic activity across the UK. Western Scotland, western England, Wales, south-western Cornwall and the area off the coast of the south-eastern England are the areas of highest activity. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free.

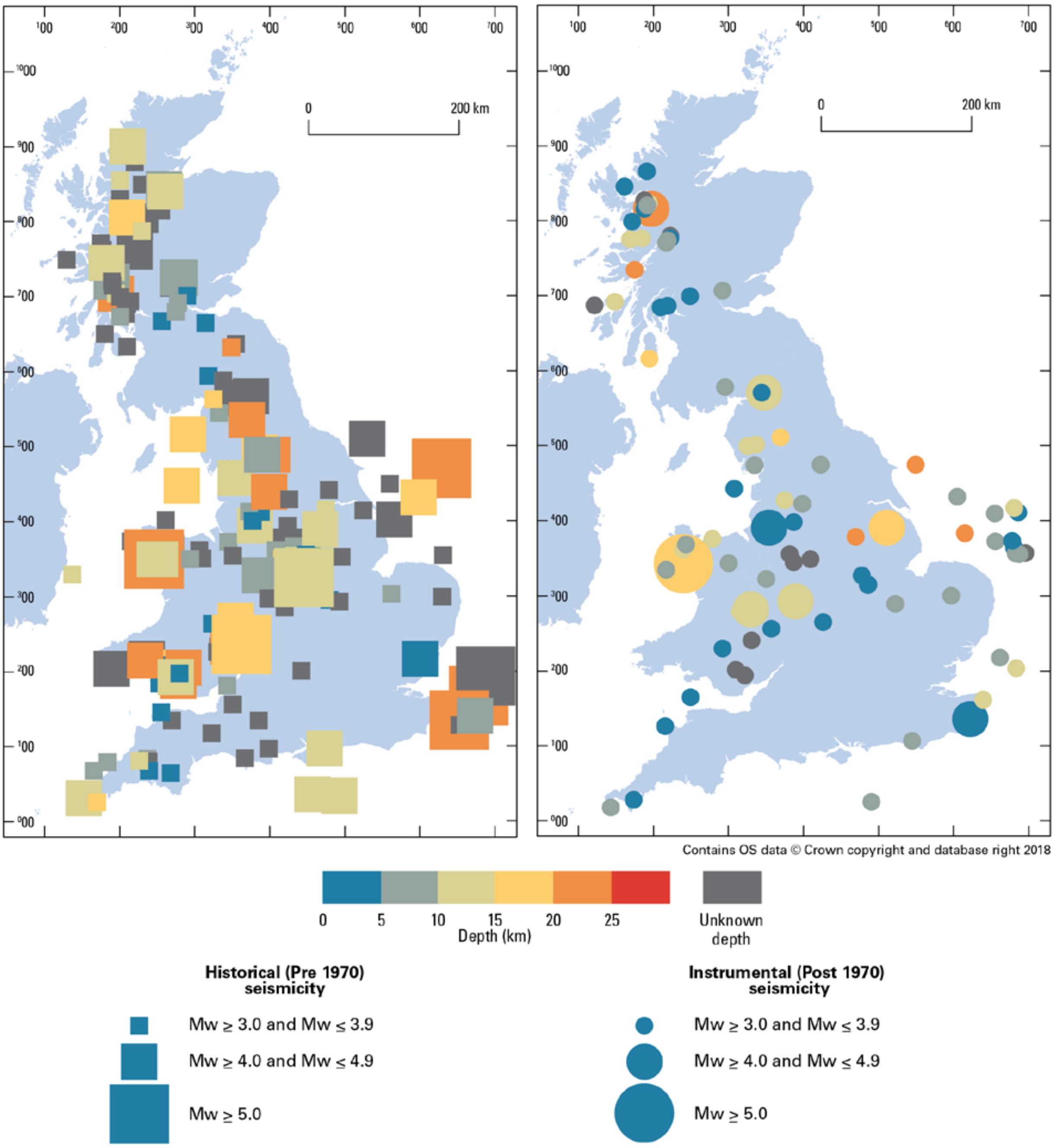


Figure 35 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

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

The largest earthquake in the catalogue is the 7 June 1931 Mw 5.9 event in the Dogger Bank area (Neilson et al., 1984). This is the largest UK earthquake for which a reliable magnitude can be estimated. The largest onshore instrumental earthquake in the UK is the 19 July 1984 Mw 5.1 event near Yr Eifel in the Lleyn

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

7.4.3 Earthquake depths

No earthquake in the UK recorded either historically or instrumentally is known to have produced a surface rupture. Typical fault dimensions for the largest recorded British earthquakes are of the order of 1 to 2 km. Therefore, it is difficult to accurately associate earthquakes with specific faults, particularly at depth, where the fault distributions and orientations are unclear and because of the uncertainties associated with depth estimates. The uncertainties in the focal depths determined for earthquakes are generally large, up to a standard deviation of ±10 km. Figure 36 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.

7.4.4 Maximum magnitude

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

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

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

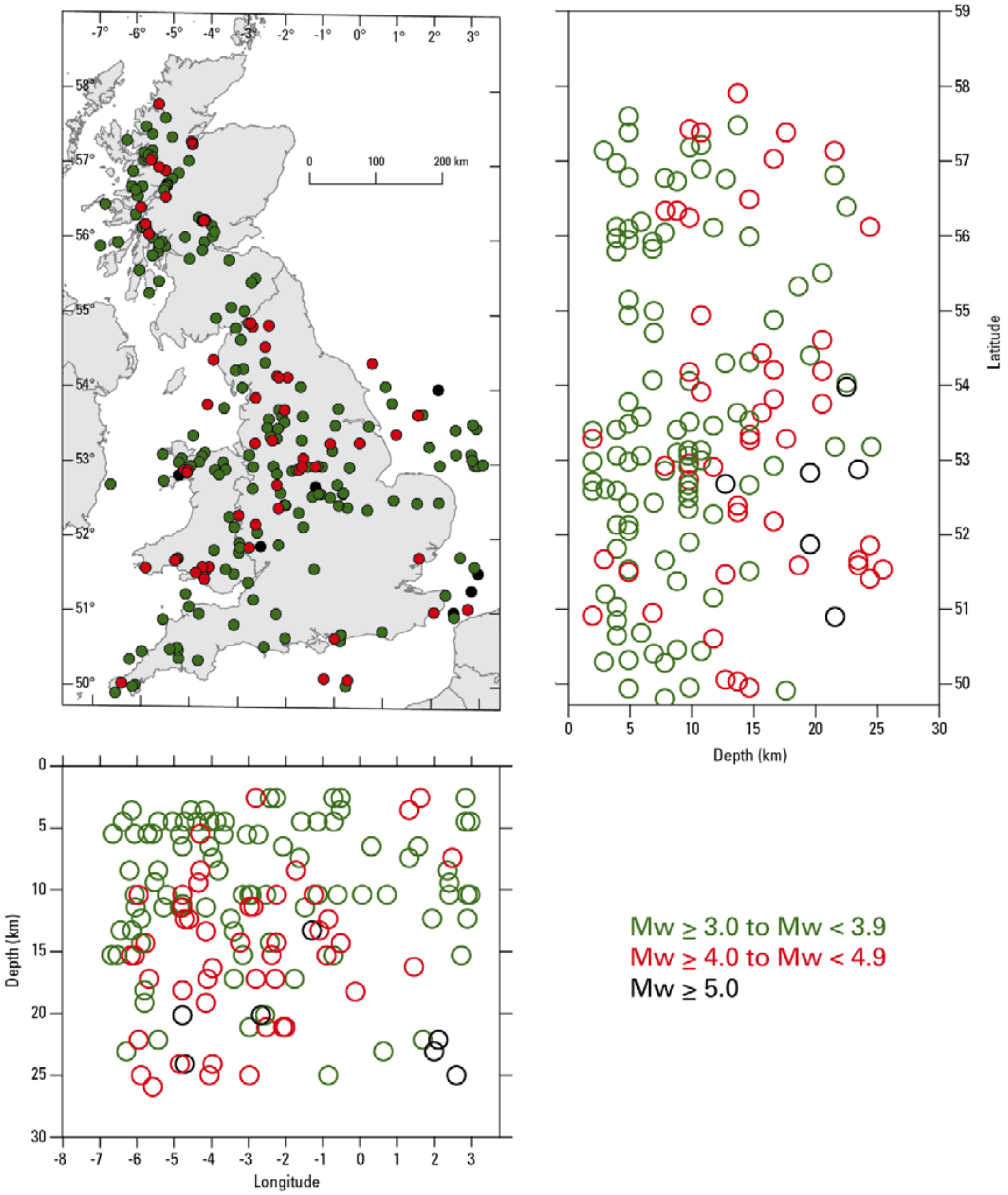


Figure 36 Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

7.4.5 Earthquake activity rates

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

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

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

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

7.4.6 Impact of future glaciation

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

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

7.4.7 Conclusions

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

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

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

7.4.8 A regional perspective

Figure 37 shows earthquake activity in the Bristol and Gloucester region. There are no records of earthquakes with magnitudes of 4 Mw or greater in this small region and only a few smaller earthquakes. The epicentre of the 1896 Hereford earthquake (5 Mw) is just outside this region. The felt area of this earthquake covered almost all of England and Wales. The epicentre was 6 km east of Hereford and significant damage was caused to the cathedral and other churches, and more than 200 chimneys (Davison, 1899; Musson, 1994).

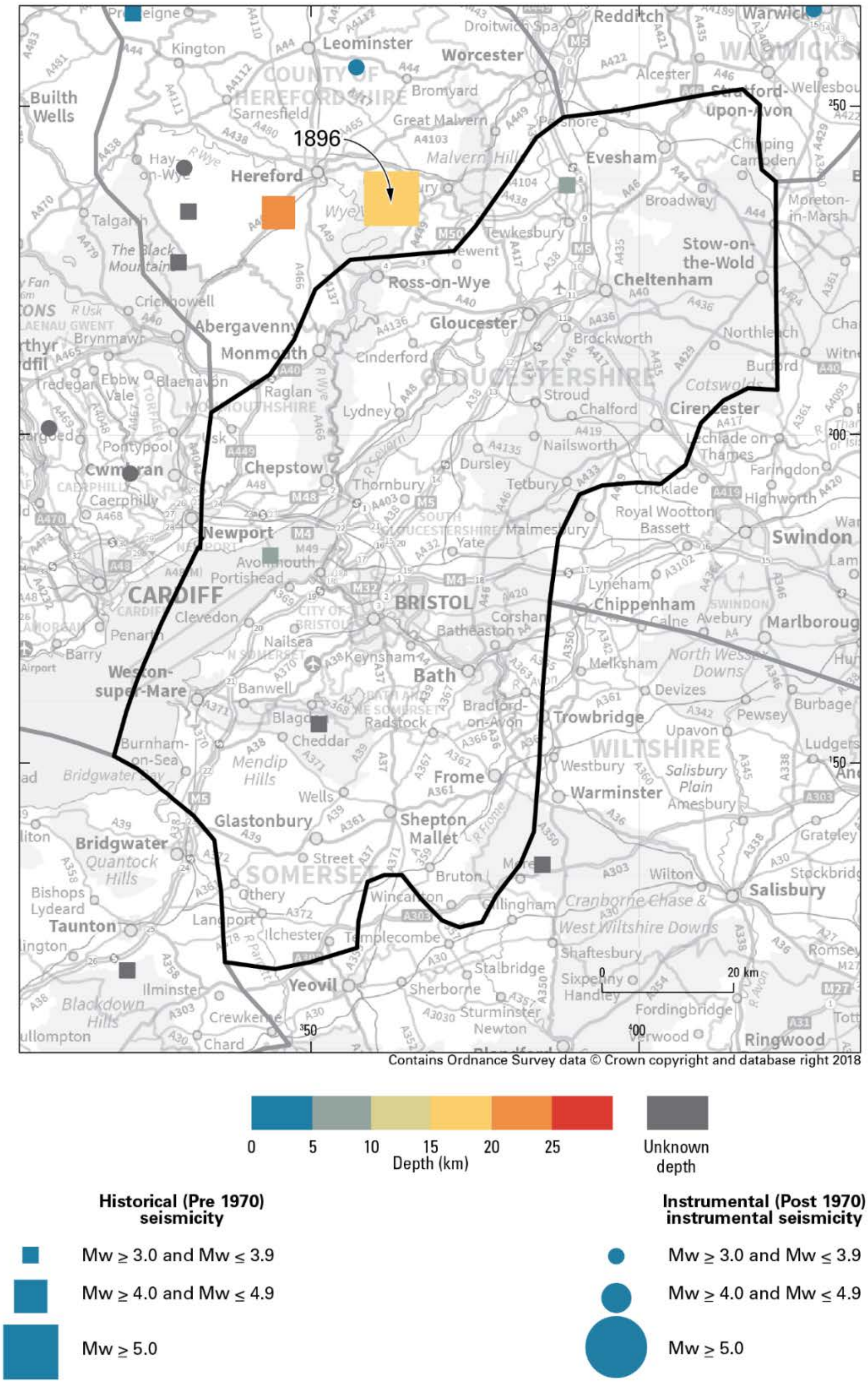


Figure 37 Historical and instrumentally recorded earthquakes in the Bristol and Gloucester region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

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

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

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

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

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

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

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

8.2 OVERVIEW OF RESOURCES IN THE REGION

Figure 38 shows the distribution of mineral resources in the region. The Bristol and Gloucester region is well known for its past coal, iron and lead mining. The region has also produced building stone (Bath Stone) at shallow depths. In the west the area is prospective for shale gas/oil.

8.3 COAL AND RELATED COMMODITIES

Coal has been extensively mined in the Bristol and Somerset and Forest of Dean coalfields (Figure 40). Most of the coal in the Forest of Dean coalfield has been exploited though some shallow, small-scale mines are still operated by 'free miners' who extract low volumes of coal. No mines are now working the Bristol and Somerset coalfield. Parts of this coalfield remain unexploited and as such in situ coal remains in a number of areas.

The Bristol and Somerset coalfield has a long history of mining dating back to Roman times and reached its peak in the early 20th century. In 1948, coal was mined at 15 National Coal Board collieries. All mining ceased in 1973 with the closure of the last two pits, Kilmersdon and Writhlington.

The Forest of Dean coalfield, located east of Monmouth, underlies an area of approximately 88 km^2. It represents one of the earliest areas in Britain where coal and iron were worked. Free mining in the Forest of Dean has been in steady decline since the privatisation of the coal industry in 1994. A few small, shallow drift mines remain from which low volumes of coal are intermittently extracted for local consumption under the local traditional 'free mining' legislation. Historically many deep coal mines operated in the Forest of Dean, however, the last of these mines closed around the late 1960s and early 1970s.

There are no current licences for coal mine methane, abandoned mine methane or coal gasification in either of the coalfields. An area between Ross-on-Wye and the Severn estuary is, however, currently in the process of being licensed for exploration for coalbed methane. UK Methane had to relinquish a licence near Bath because of opposition to exploration by the public and local authorities. The prospects for mine gas drainage are perceived as poor. In many cases, the mine shafts were backfilled with colliery waste after closure and the potential for coalbed methane development from virgin coal seams in this area is very low because of the low methane content of the coal.

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 south-west of the region (see Section 4). Halite has been extracted in the past, and was discovered in a borehole drilled for coal near Puriton in Somerset in 1910 at a depth of 183 m. Brine was extracted for 11 years from this area before the works finally closed in 1922. The Somerset salt field was also explored between Puriton and Wedmore where deep boreholes have shown that salt beds occur through as much as 107 m of strata. The main salt-bearing layers are encountered between depths of 690 to 740 m below NGS datum. It is unlikely that the salt-bearing strata in Somerset will ever be worked as a source of salt because of its widespread occurrence elsewhere in England.

8.5 OTHER BEDDED AND MISCELLANEOUS COMMODITIES

There are no deposits of bedded or other miscellaneous deposits that have been worked deeper than 100 m below NGS datum in the region. However, extensive shallow workings for Bath Stone and similar Jurassic-aged buildings stones, some still operational, occur to the east and south-east of Bath extending eastwards into the north-west corner of the Hampshire Basin region at Corsham.

Fuller's Earth has previously been mined underground to the south of Bath, although all past workings were shallow.

Strontium, in the form of the evaporite mineral celestite, has been mined by open pit methods in the Yate area. No workings are active today and all past workings were shallow.

8.6 VEIN-TYPE AND RELATED ORE DEPOSITS

Areas that have undergone deep mining for vein-type ore deposits have been identified from the location of deep mine shafts and the known locations of mineral veins. In most cases, mine plans are not available or not accurate enough to delineate the surface expression of underground workings.

There are extensive iron ore deposits in the Forest of Dean that have probably been mined for iron and pigments for over 2000 years (Figure 38). The iron ores were worked from Roman times until the 1940s. On the eastern side of the Forest of Dean these ores were exploited to depths greater than 100 m below NGS datum at several mines in the Coleford area during the 19th and 20th centuries. The other parts of the iron orefield have not been worked as deep, although there are numerous old workings present. Recorded output between 1842 and 1940 is about 4.8 million tonnes of ore. Reserves are effectively exhausted and the deposits are no longer considered of economic significance as a source of iron ore, though small quantities of pigments are still produced underground at Clearwells.

The Mendip Hills are an ancient lead and zinc mining area with a history of mining going back around 2000 years. Both lead and zinc have been mined in the orefield from at least as early as the Roman occupation through to the early 20th century. The mines were generally small and, while most pre-date any legislative requirements to maintain plans, none are known or suspected to be deeper than 100 m below NGS datum.

The orefields shown on Figure 38 delineate the areas where most of the known mineralisation is located, however, large parts of the orefield areas are not intensively mineralised and have not been extensively mined or mined to depths exceeding 100 m below NGS datum. Because of the widespread distribution of mineral veins and the extent of past, shallow mine workings in these areas, the mineral potential may be re-examined in the future.

There are also known mineral veins that have been mined in the past outside the main orefield areas but most of these have not been extensively mined or mined to depth.

8.7 HYDROCARBONS (OIL AND GAS)

There are no conventional hydrocarbon fields on or offshore in the region. A number of wells have been drilled without encouraging signs of economic quantities of hydrocarbons.

In the Bristol–Somerset basin and the Forest of Dean coalfield, a potential shale gas resource is located in mudrocks of Namurian and Tournaisian–Visean age. These coalfields are, however, considered to have very limited potential for virgin coalbed methane production because they probably contain low volumes of coalbed methane, at least at shallower depths.

8.8 GAS STORAGE

There are no planned, under construction or operating underground gas storage facilities in the region. British Gas drilled a series of boreholes around Stow-on-the-Wold to assess the area for underground gas storage but subsequently abandoned the project.

There seems little immediate prospect for gas storage in the region, with any potential probably lying in lined or unlined caverns in hard rock locations.

8.9 GEOTHERMAL ENERGY

There are no deep geothermal heating systems currently operating in the Bristol and Gloucester region. The thermal springs at Bath are sourced from a fault penetrating into deeply buried limestones, however, exploitation of the waters as a heat resource is unlikely due to potential negative effects on the springs' natural discharge and the intrinsic historical and tourist value of the thermal springs.

The Gloucester–Worcester area is underlain by the thick sedimentary succession of the Worcester basin, including the Sherwood Sandstone Group brine aquifer. Regional mapping of the Worcester basin has inferred that, in the deeper-buried areas of the basin, the Sherwood Sandstone Group could reach up to around 2500 m depth and potentially reach around 50 to 60ºC at its base. Although not nationally significant, the area has potential for local heating schemes.

There is the potential for minor district heating schemes using ground-sourced heat pumps in abandoned mine workings, especially from deep mines in the Forest of Dean coalfield. However, many mines were backfilled and as yet no schemes have been implemented.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are small clusters of deep (greater than 200 m below NGS datum) boreholes in the region (Figure 39). Most of these have been drilled during the course of exploration for and the evaluation of mineral deposits, particularly coal, and as such, the highest concentration of boreholes are located on the various coalfields.

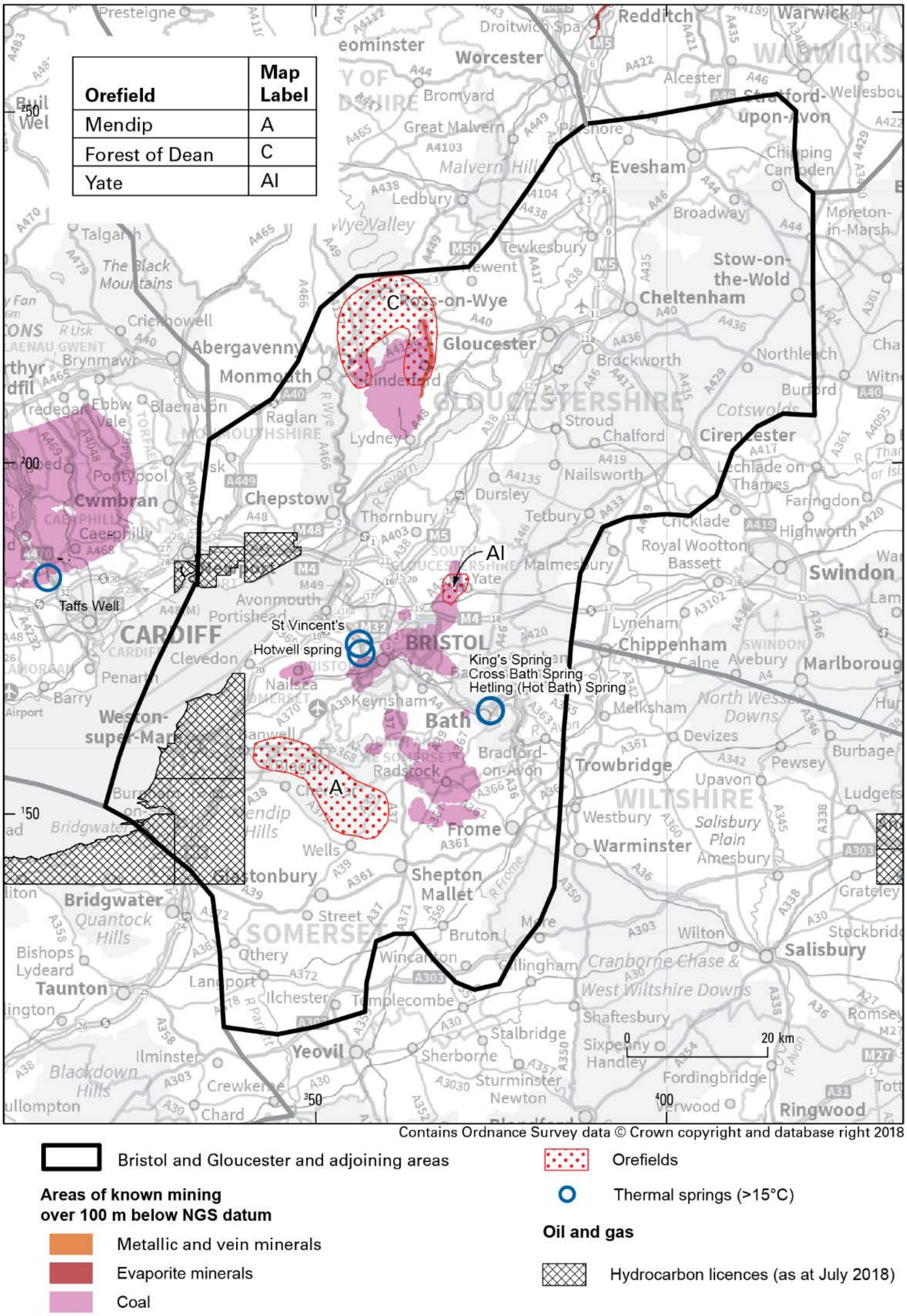


Figure 38 Distribution of mineral resources in the region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields and underground gas storage licence areas are not shown. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

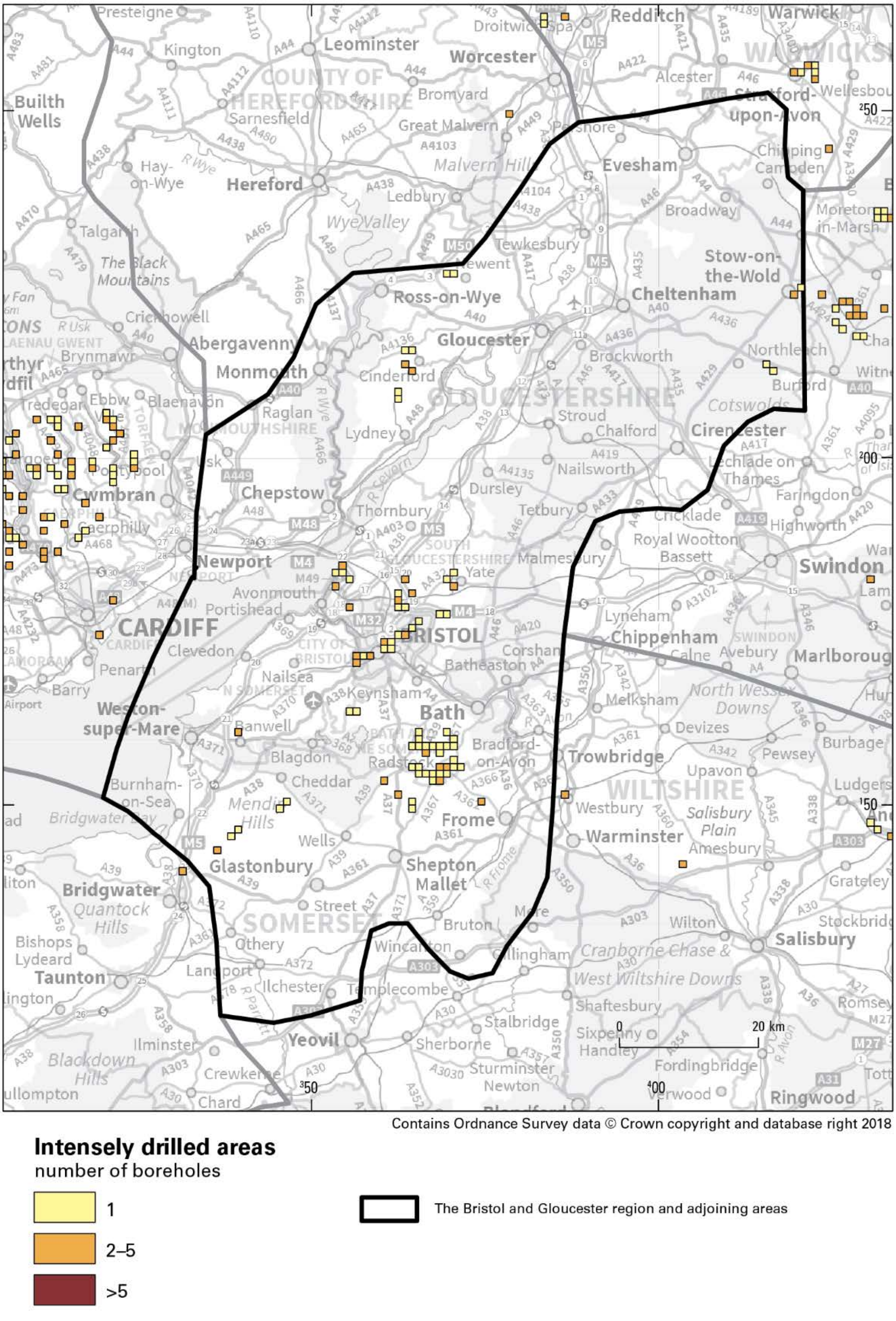


Figure 39 Location of intensely drilled areas in the Bristol and Gloucester region, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

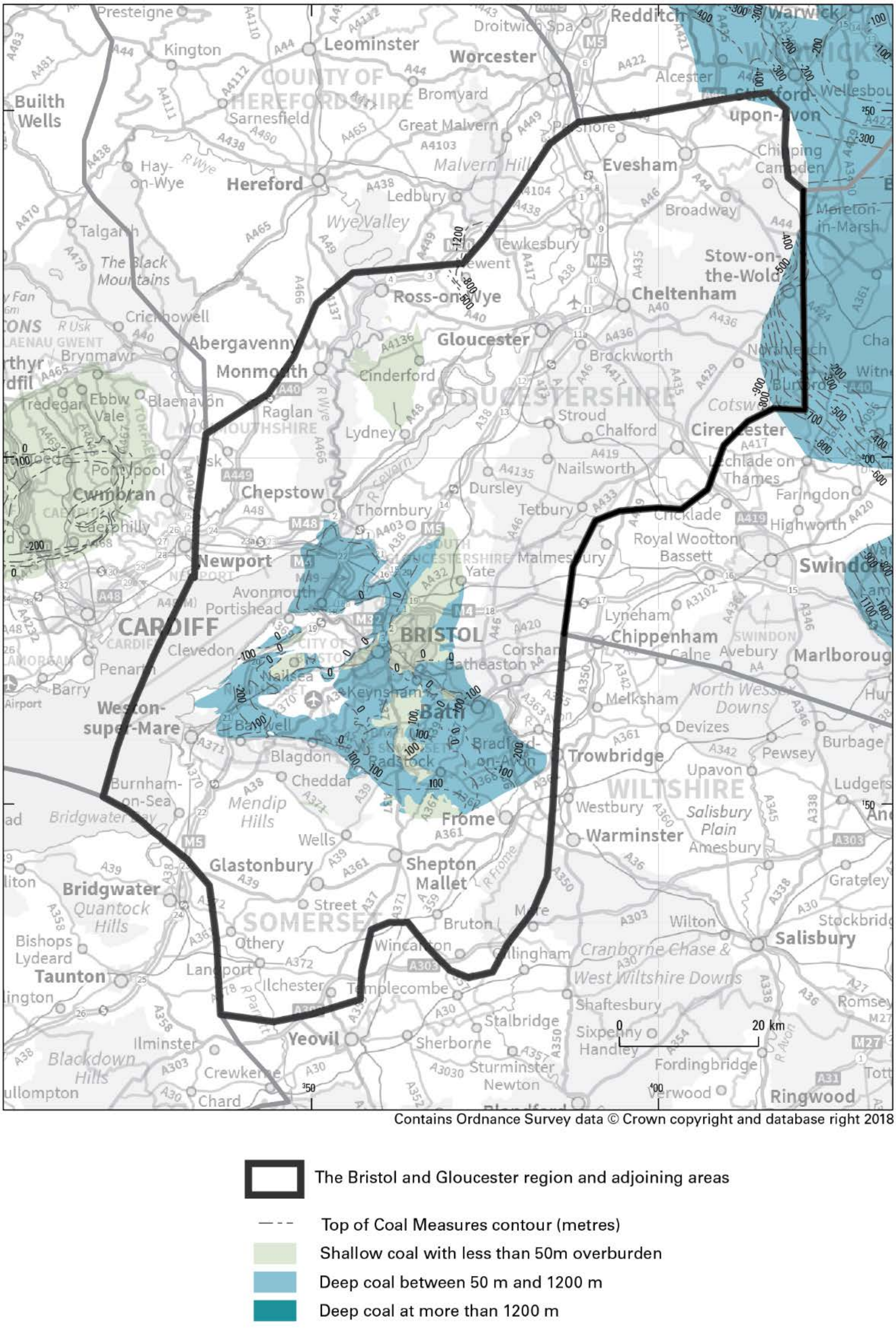


Figure 40 Distribution of coal resources in the Bristol and Gloucester region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

8.11 SUPPORTING INFORMATION

The location of deep mines is based on mine plans, reported locations and depths of historic mines, mapped mineral veins and areas of mineralisation. Mining has taken place in the UK since pre-Roman times. With such a long history, mines may exist that have not been identified and therefore not included within the comprehensive review used to create this dataset. However, it is unlikely these mines will be sufficiently deep to be of concern for NGS. It is also possible that mapped mineral veins do not accurately present the subsurface extent of underground workings. A buffer of 100 m has been applied to all mapped mineral veins to mitigate for this.

8.11.1 Mine depths

Any reported mine depth is often difficult to attribute to a specific datum. This results in a degree of uncertainty about the maximum depth of workings. For example, depths are variously reported as being from surface or adit (or adits) but it is often unclear which is being used and in which area of a mine. Significant additional research, including of historic mine plans and records, would be required to overcome this uncertainty. A pragmatic solution to this issue has been to assume that reported depths are to the bottom of the deepest adit unless otherwise stated.

Many mine shafts are not vertical or are vertical for only part of their total depth. For the purposes of this assessment it has been assumed that all depths are vertical. This will slightly over estimate depths where this is not the case.

Mine workings have been grouped in clusters where they are known or likely to be interconnected at depth through common workings or vein structures and the maximum known depth for the group of mines has been applied.

Most mine shaft depths are quoted in fathoms, some in feet and a few in metres. The conversion factors used in this assessment are:

1 fathom = 6 feet
1 foot = 0.3048 metres

Depths in metres have been rounded to the nearest whole metre.

There is frequently uncertainty about actual depths of shafts. Where more than one depth is quoted the deepest depth has been used unless there is evidence that this was an error. Again this will be conservative and present an overestimate of actual depth.

8.11.2 Mined extents

The areas of vein-type and related ore deposits shown on Figure 38 have been depicted where possible by applying a 100 m-wide buffer to the mapped extent of the mineral vein. Where this is not possible, a 100 m buffer has been applied the location of known mines in order to encompass the possible extent of the workings. This approach ensures that any inaccuracies in the mapped vein locations and extent of past workings fall within the boundary of the area identified.

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

8.11.3 Potash, halite, gypsum/anhydrite and polyhalite deposits

The 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.

8.11.4 Hydrocarbons (oil and gas)

The hydrocarbon licence areas displayed on Figure 38 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 and licence areas can change over time.

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.

8.11.5 Coal and related commodities

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

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

8.11.6 Borehole depths

Not all boreholes are drilled vertically. Some are inclined and others, mainly for hydrocarbon exploitation, are deviated, sometimes with multiple boreholes branching from a single initial borehole. The 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.* (London: British Geological Survey for the Department of Energy and Climate Change.)

BARRON, A J M, SHEPPARD, T H, GALLOIS, R W, HOBBS, P R N, and SMITH, N J P. 2011. Geology of the Bath District. *Sheet Explanation of the British Geological Survey*. Sheet 265 (England and Wales).

BARRON, A J M, LOTT, G K, and RIDING, J B. 2012. Stratigraphic 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, IVIMEY-COOK, H C, and LOTT, G K. 1993. The Purse Caundle Borehole, Dorset: stratigraphy and sedimentology of the Inferior Oolite and Fuller's Earth in the Sherborne area of the Wessex basin. *British Geological Survey Research Report,* SA/93/01.

BARTON, C M, STRANGE, P J, ROYSE, K R, and FARRANT, A R. 2002. Geology of the Bristol District. *Sheet Explanation of the British Geological Survey*. Sheet 264 (England and Wales).

BENTON, M, COOK, E, and TURNER, P. 2002. Permian and Triassic Red Beds and the Penarth Group of Great Britain. *Geological Conservation Review Series*, No. 24. (Peterborough: Joint Nature Conservation Committee.)

BRENCHLEY, P J, and RAWSON, P F (editors). 2006. The geology of England and Wales. (London: The Geological Society.)

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).

CAMERON, T D J, CROSBY, A, BALSON, P S, JEFFERY, D H, LOTT, G K, BULAT, J, and HARRISON, D J. 1992. *United Kingdom Offshore Regional Report: The Geology of the Southern North Sea*. (London: HMSO.)

CHADWICK, R A, and EVANS, D J. 1995. The timing and direction of Permo-Triassic extension in southern Britain. *Geological Society of London Special Publication*, No. 91(1), 161–192.

CHADWICK, R A, and EVANS, D J. 2005. A seismic atlas of southern Britain: images of subsurface structure. *Occasional Publication of the British Geological Survey*, 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, 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/11/06*.

GALLOIS, R W. 2001. The stratigraphy of the Mercia Mudstone Group (Mid to Late Triassic) of the south Devon coast. *Geoscience in south-west England*, Vol. 10, 195–204.

GREEN, G W. 1992. *British regional geology: Bristol and Gloucester region*. (Third edition) (London: HMSO: British Geological Survey.)

GREEN, G W. 2008. Volcanic stratigraphical architecture of the east Mendip Silurian inlier, Somerset, UK. *Proceedings of the Geologists' Association, Vol.* 119, 339–350.

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.

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.

KELLAWAY, G A, WELCH, F B A, and IVIMEY-COOK, H C. 1993. Geology of the Bristol district. *Memoir of the British Geological Survey*, 1:63 360 special sheet (England and Wales).

PENN, I E. 1982. Middle Jurassic stratigraphy and correlation of the Winterborne Kingston Borehole, Dorset. 53–76 in *The Winterborne Kingston Borehole, Dorset, England*. RHYS, G H, LOTT, G K, and CALVER, M A (editors). Report of the Institute of Geological Sciences. (London: HMSO for Institute of Geological Sciences.)

PENN, I E, and WYATT, R J. 1979. The stratigraphy and correlation of Bathonian strata in the Bath-Frome area. *Report of the lnstitute of Geological Sciences*. No.78/22, 25–88.

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.

SELLWOOD, B W, SHEPHERD, T J, EVANS, M R, and JAMES, B. 1989. Origin of late cements in oolitic reservoir facies: a fluid inclusion and isotopic study (Mid Jurassic, southern England). *Sedimentary Geology*, Vol. 61, 223–237.

SIMMS, M J, CHIDLAW, N, MORTON, N, and PAGE, K N. 2004. British Lower Jurassic Stratigraphy. *Geological Conservation Review Series*, No. 30. (Peterborough: Joint Nature Conservation Committee.)

SMITH, D B, AND FRANCIS, E A. 1967. Geology of the Country between Durham and west Hartlepool, *Memoir of the British Geological Survey*, Sheet 27 (England and Wales).

SUMBLER, M G, BARRON, A J M, and MORIGI, A N. 2000. Geology of the Cirencester district. *Memoir of the British Geological Survey*, Sheet 235 (England and Wales).

WARRINGTON, G, and eight others. 1980. A correlation of Triassic rocks in the British Isles. *Special Report of the Geological Society of London*, No. 13.

WATERS, C N, WATERS, R A, BARCLAY, W J, and DAVIES, J R. 2009. A lithostratigraphical framework for the Carboniferous successions of southern Great Britain (onshore). *British Geological Survey Research Report*, RR/09/001.

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.

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

WHITTAKER, A, and GREEN, G W. 1983. Geology of the country around Weston-super-Mare. *Memoir of the Geological Survey of Great Britain*. Sheet 279 (England and Wales). (London: HMSO for the Institute of Geological Sciences.)

WHITTAKER, A, and IVIMEY-COOK, H C. 1972. Geology of Bredon Hill, Worcestershire. *Bulletin of the geological survey of Great Britain*, Vol. 42, 1–49.

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.

ANDERSON, J G C, and OWEN, T R. 1968. The structure of the British Isles. (Oxford; New York: Pergamon Press.)

BARCLAY, W J, AMBROSE, K, CHADWICK, R A, and PHARAOH, T C. 1997. Geology of the country around Worcester. *Memoir of the British Geological Survey*. Sheet 199 (England and Wales).

BARRON, A J M, SHEPPARD, T H, GALLOIS, R W, HOBBS, P R N, and SMITH, N J P. 2011. Geology of the Bath District. *Sheet Explanation of the British Geological Survey*. Sheet 265 (England and Wales).

BARTON, C M, STRANGE, P J, ROYSE, K R, and FARRANT, A R. 2002. Geology of the Bristol District. *Sheet Explanation of the British Geological Survey*. Sheet 264 (England and Wales).

BOYER, S E, and ELLIOTT, D. 1982. Thrust systems. *American Association of Petroleum Geologists Bulletin*, Vol. 66, 1196–1230.

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

BROOKS, M, TRAYNER, P M, and TRIMBLE, T J. 1988. Mesozoic reactivation of Variscan thrusting in the Bristol Channel area, UK. *Journal of the Geological Society of London*, Vol. 145, 439–444.

CAVE, R. 1977. Geology of the Malmesbury district. *Memoir of the British Geological Survey*, Sheet 251 (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, and EVANS, D J. 1995. The timing and direction of Permo-Triassic rifting in southern Britain. 161–192 *in* Permo-Triassic Rifting in the UK. BOLDY, S R, and HARDMAN, R F P (editors). *Geological Society of London Special Publication*, No 91.

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

CHADWICK, R A, and SMITH, N J P. 1988. Evidence of negative structural inversion beneath central England from new seismic reflection data. Short Paper. *Journal of the Geological Society of London*, Vol. 145, 519–522.

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.

DONATO, J. 1988. Possible Variscan thrusting beneath the Somerton anticline, Somerset. *Journal of the Geological Society of London*, Vol. 145, 431–438.

DUNNING, F W. 1992. Structure. 523-561 in *Geology of England and Wales*. DUFF, P McL D, and SMITH, A J (editors). (London: The Geological Society.)

GREEN, G W. 1992. *British regional geology: Bristol and Gloucester region*. (Third edition) (London: HMSO: British Geological Survey.)

GREEN, G W, and WELCH, F B A. 1965. Geology of the country around Wells and Cheddar. *Memoir of the Geological Survey of Great Britain*, Sheet 280 (England and Wales). (London: HMSO for the Institute of Geological Sciences.)

HANCOCK P L, DUNNE, W M, and TRINGHAM, M E. 1983. Variscan deformation in south-west Wales. 47–73 in *The Variscan fold belt in the British Isles*. HANCOCK, P L (editor). (Bristol: Adam Hilger.)

HOLLOWAY, S, and CHADWICK, R A. 1984. The IGS Bruton Borehole (Somerset, England) and its regional structural significance. *Proceedings of the Geologists' Association*, Vol. 95, 165–174.

KELLAWAY, G A, and HANCOCK, P L. 1983. Structure of the Bristol district, the Forest of Dean and the Malvern fault zone. 88–107 in *The Variscan fold belt in the British Isles*. HANCOCK, P L (editor). (Bristol: Adam Hilger.)

KELLAWAY, G A, CROOKALL, R, and WELCH, F B A. 1948. *British regional geology: Bristol and Gloucester region*. (Second edition) (London: HMSO: British Geological Survey.)

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, 347–378.

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

MILIORIZOS, M, RUFFELL, A, and BROOKS, M. 2004. Variscan structure of the inner Bristol Channel, UK. *Journal of the Geological Society of London*, Vol. 161, 31–44.

PHARAOH, T C, and CARNEY, J. 2000. Introduction to the Precambrian rocks of England and Wales. 1–15 *in* Precambrian rocks of England and Wales. *Geological Conservation Review Series,* No 20. (Peterborough: Joint Nature Conservation Committee.)

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.

PHARAOH, T C, MERRIMAN, R J, WEBB, P C, and BECKINSALE, R D. 1987a. The concealed Caledonides of eastern England: preliminary results of a multidisciplinary study. *Proceedings of the Yorkshire Geological Society*, Vol. 46, 355–369.

PHARAOH, T C, WEBB, P C, THORPE, R S, and BECKINSALE, R D. 1987b. Geochemical evidence for the tectonic setting of late Proterozoic volcanic suites in the central UK. 541–552 in Geochemistry and mineralisation of Proterozoic volcanic suites. PHARAOH, T C, BECKINSALE, R D, and RICKARD, D T (editors). *Geological Society of London Special Publication*, No. 33.

SMITH, N J P, KIRBY, G A, and PHARAOH, T C. 2005. Structure and evolution of the south-west Pennine basin and adjacent area. *Subsurface Memoir of the British Geological Survey.*

TAPPIN, D R, CHADWICK, R A, JACKSON, A A, WINGFIELD, R T R, and SMITH, N J P. 1994. *United Kingdom offshore regional report: Geology of Cardigan Bay and the Bristol Channel.* (London: HMSO for the British Geological Survey.)

WELCH, F B A, and TROTTER, F M. 1961. Geology of the Country around Monmouth and Chepstow. *Memoir of the Geological Survey of Great Britain*. Sheets 233 and 250. (London: HMSO.)

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

WHITTAKER, A, and GREEN, G W. 1983. Geology of the country around Weston-super-Mare. *Memoir of the Geological Survey of Great Britain*. Sheet 279 (England and Wales). (London: HMSO for the Institute of Geological Sciences.)

WILLIAMS, G D, and CHAPMAN, T J. 1986. The Bristol–Mendip foreland thrust belt. *Journal of the Geological Society of London,* Vol. 143, 63–73.

Groundwater

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.

ALDOUS P J, SMART, P L, and BLACK, J A. 1986. Groundwater management problems in abandoned coal-mined aquifers: a case study of the Forest of Dean, England. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 19, 375–388.

ANDREWS, J N. 1991. Radioactivity and dissolved gases in the thermal waters of Bath. 157–170 in *Hot Ssprings of Bath.* Kellaway, G (editor). (Bath: Bath City Council.)

ANDREWS, J N, BURGESS, W G, EDMUNDS, W M, KAY, R L F, and LEE, D J. 1982. The Thermal Springs of Bath. *Nature,* V. 298, 339–343.

BARCLAY, W J, AMBROSE, K, CHADWICK, R A, and PHARAOH, T C. 1997. Geology of the country around Worcester. *Memoir of the British Geological Survey*. Sheet 199 (England and Wales).

BARRON, A J M, SUMBLER, M G, and MORIGI, A N. 2002. Geology of the Moreton-in-Marsh district. *Sheet description of the British Geological Survey.* Sheet 217 (England and Wales).

BARRON, A J M, SHEPPARD, T H, GALLOIS, R W, HOBBS, P R N, and SMITH, N J P. 2011. Geology of the Bath District. *Sheet Explanation of the British Geological Survey*. Sheet 265 (England and Wales).

BARTON, C M, STRANGE, P J, ROYSE, K R, and FARRANT, A R. 2002. Geology of the Bristol District. *Sheet Explanation of the British Geological Survey*. Sheet 264 (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. *Memoir of the British Geological Survey*. Sheet 297 (England and Wales).

BRITISH GEOLOGICAL SURVEY, 2016. *The BGS Lexicon of Named Rock Units.* [Online]. Available at: http://www.bgs.ac.uk/lexicon/lexicon

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, DARLING, W G, PURTSCHERT, R, and CORCHO ALVARADO, J A. 2014. Noble gas, CFC and other geochemical evidence for the age and origin of the Bath thermal waters, UK. *Applied Geochemistry,* Vol. 40, 155–163.

ENVIRONMENT AGENCY, 2004. *Groundwater Quality Review: Jurassic Limestone.* (Bristol: Environment Agency.)

ENVIRONMENT AGENCY. 2013. *Groundwater Protection: Principles and practice (GP3)*. (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.

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

GREEN, G W, and WELCH, F B A. 1965. Geology of the country around Wells and Cheddar. *Memoir of the Geological Survey of Great Britain,* Sheet 280 (England and Wales). (London: HMSO for the Institute of Geological Sciences.)

HAWKINS, A B, and KELLAWAY, G A. 1991. The hot springs of the Avon Gorge, Bristol. 179–204 in *The Hot Springs of Bath.* KELLAWAY, G A (editor). (Bath: City of Bath Council.)

HOBBS, P R N, HALLAM, J R, FORSTER, A, ENTWISLE, D C, JONES, L D, CRIPPS, A C, NORTHMORE, K J, SELF, S J, and MEAKIN, J L. 2002. *Engineering geology of British rocks and soils: mudstones of the Mercia Mudstone Group,* Keyworth, Nottingham: British Geological Survey.

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.

KELLAWAY, G A. 1991. Investigation of the Bath Hot springs (1977–1987). 97–126 in *The Hot Springs of Bath.* KELLAWAY, G A (editor). (Bath: City of Bath Council.)

MCCANN, C, MANN, A C, MCCANN, D M, and KELLAWAY, G A. 2013. Insights into the origin of the thermal springs of Bath and Bristol, England, from geophysical data. *Quarterly Journal of Engineering Geology and Hydrogeology,*Vol. 46(3), 267–279.

MOREAU, M F, SHAND, P, WILTON, N, BROWN, S, and ALLEN, D. 2004. The Devonian aquifer of South Wales and Herefordshire. Baseline Report Series. Baseline Report Series: 12. *British Geological Survey Commissioned Report,* CR/04/185N.

MORGAN-JONES, M, and EGGBORO, M D. 1981. The hydrogeochemistry of the Jurassic limestones in Gloucestershire, England. *Quarterly Journal of Engineering Geology and Hydrogeology,* Vol. 14, 25–39.

NEUMANN, I, BROWN, S, SMEDLEY, P, and BESIAN, T. 1999. The Great and Inferior Oolite of the Cotswolds District. Baseline Report Series: 7. *British Geological Survey Commissioned Report,* CR/03/202N.

RICHARDSON L, 1930, Wells and springs of Gloucestershire, *Memoirs of the Geological Survey of Great Britain. (*London: HMSO)

SHAND, P, ANDER, E L, GRIFFITHS, K J, DOHERTY, P, and LAWRENCE, A R. 2004. The Bridport Sands of Dorset and Somerset. Baseline Report Series: 11. *British Geological Survey Commissioned Report,* CR/04/166N

STANTON W, 2004, Intertidal warm springs of the Avon Gorge, Nature in Avon, 64, 29-31.

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

WHITTAKER, A, and GREEN, G W. 1983. Geology of the country around Weston-super-Mare. *Memoir of the Geological Survey of Great Britain*. Sheet 279 (England and Wales). (London: HMSO for the Institute of Geological Sciences.)

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*. 2. 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.)

DAVISON, C. 1899. *The Hereford earthquake of December 17, 1896*. (Birmingham: Cornish Brothers).

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*. (Chichester, UK: 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.

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.

Coal resources

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

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

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

Other bedded mineral resources

The locations of mineral resources has been taken from BGS mineral resources maps for England (http://www.bgs.ac.uk/mineralsuk/planning/resource.html#MRM) and the BGS BRITPITS database of mines and quarries.

Geothermal energy resources

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

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

Metallic mineral resources

The locations of deep mines for metallic minerals have been sourced from BGS economic memoirs such as:

TROTTER, F M. 1942. Geology of the Forest of Dean coal and iron orefield. *Memoirs of the Geological Survey of Great Britain.*

Other information on deep mineral resources has been taken from BGS mineral resources maps for England (http://www.bgs.ac.uk/mineralsuk/planning/resource.html#MRM), the BGS BRITPITS database of mines and quarries and the BGS 1:1,500,000 Metallogenic Resources Map

Hydrocarbon resources

The locations of on-shore 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/