National Geological Screening: South-west England region

Minerals and Waste Programme

Commissioned Report CR/17/095

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/095

National Geological Screening: South-west England region

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Foreword

This report is the published product of one of a series of studies covering England, Wales and Northern Ireland commissioned by Radioactive Waste Management (RWM) Ltd. The report provides geological information about the South-west England region to underpin the process of national geological screening set out in the UK Government's White Paper *Implementing geological disposal: a framework for the long-term management of higher activity radioactive waste* (DECC, 2014). The report describes geological features relevant to the safety requirements of a geological disposal facility (GDF) for radioactive waste emplaced onshore and up to 20 km offshore at depths between 200 and 1000 m from surface. It is written for a technical audience but is intended to inform RWM in its discussions with communities interested in finding out about the potential for their area to host a GDF.

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Acronyms and abbreviations

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

Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

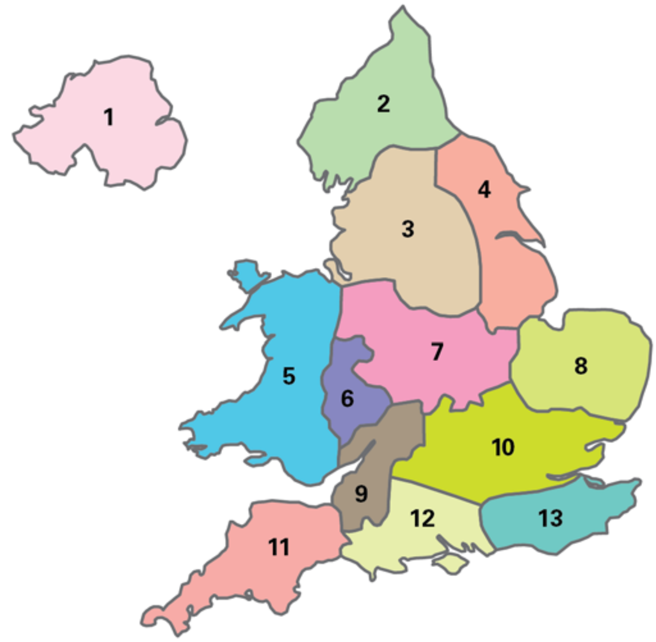
Principal aquifer — a regionally important aquifer defined by the Environment Agency as layers of rock that have high intergranular and/or fracture permeability, meaning they usually provide a high level of water storage (Environment Agency, 2013).

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

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

1 Introduction

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



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

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

2 Background

2.1 NATIONAL GEOLOGICAL SCREENING GUIDANCE

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

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

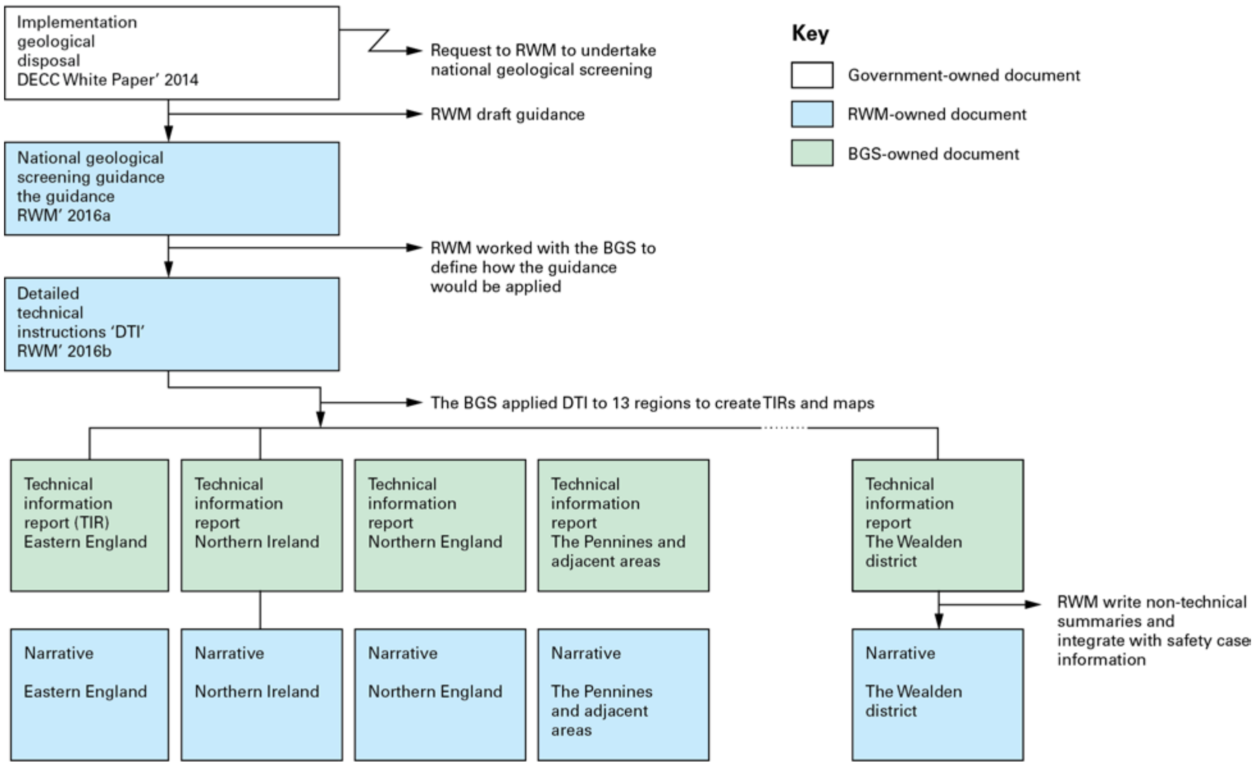


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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

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

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

2.2 DETAILED TECHNICAL INSTRUCTIONS

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

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

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

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

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

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

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

i. **Rock type**

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

ii. **Rock structure**

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

iii. **Groundwater**

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

iv. **Natural processes**

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

v. **Resources**

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

3 The South-west England region

This region lies south-west of a line running approximately from Minehead to Lyme Regis, and includes the whole of Devon and Cornwall, and part of Somerset, forming the South-west England peninsula.

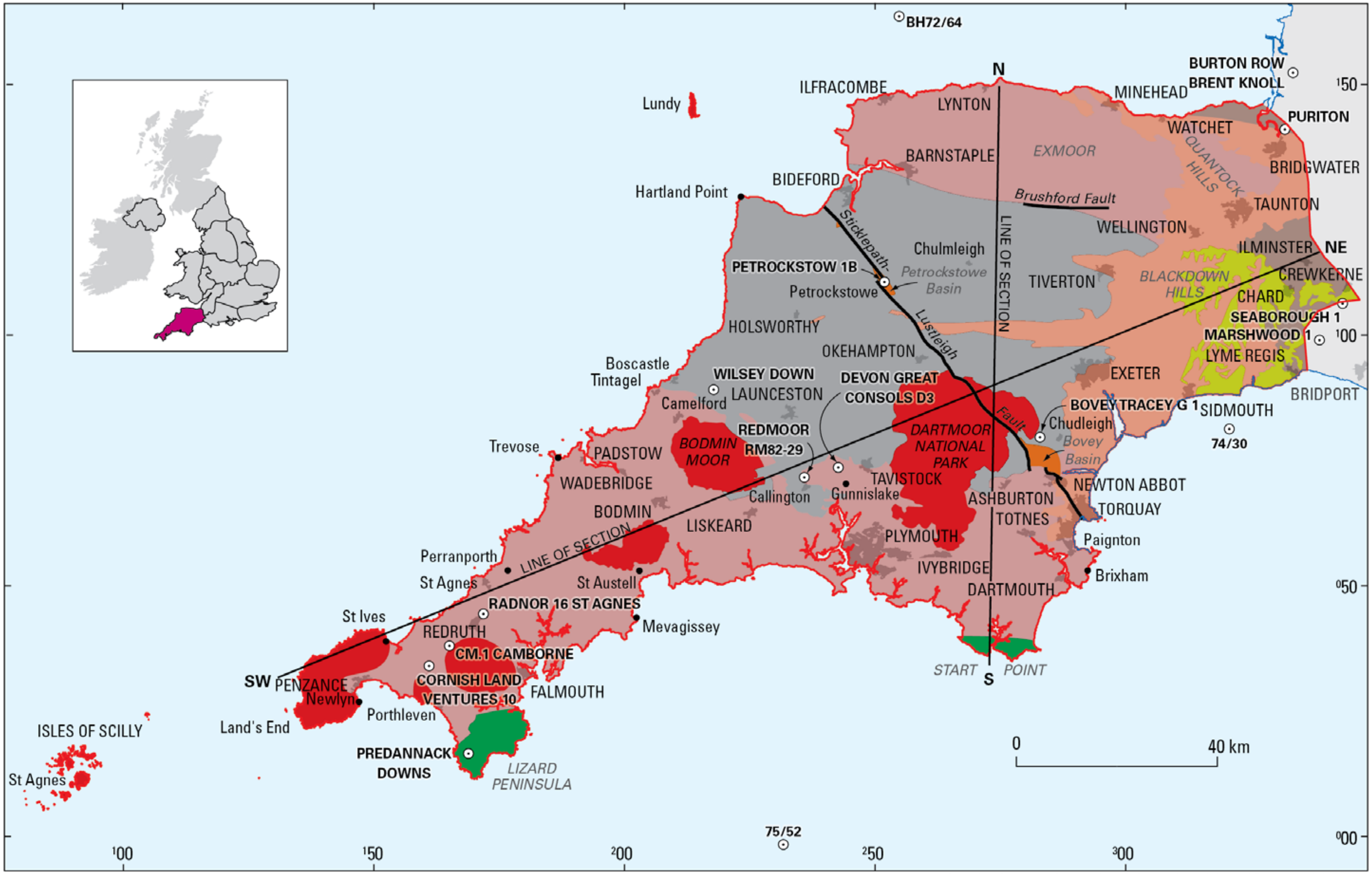
The region divides broadly into two landscape types, associated with the bedrock geology. Cornwall and west Devon are characterised by a rolling landscape with broadly west–east aligned ridges associated with the structural 'grain' in the Devonian and Carboniferous bedrock (sometimes referred to as 'basement rock') (Figure 3). The typical coastal profile is 20–30 m of rugged cliffs backed by steep coastal slopes rising to 100–150 m, with intervening pocket bays. The east Devon and Somerset landscape, by contrast, comprises a series of escarpments, plateaux and intervening low-lying vales associated with the younger Mesozoic and Cenozoic 'sedimentary cover' strata. The coastal profile varies from subvertical cliffs rising to in excess of 100 m to low-lying stretches, depending on the nature of the bedrock.

The surface and shallower geology (to about 200 m depth) of the region is well known from exposure of rocks in natural outcrops — in particular, in cliffs and rock platforms around the coast — and in quarries and mines. The last two relate to both building stone (e.g. slate, granite and limestone) extraction and metalliferous mining (e.g. copper, tin, arsenic). Knowledge of the deeper geology of the region comes largely from a small number of deeper boreholes, mainly associated with mineral exploration around the Cornubian granite batholiths in the south-west of the region and also with geothermal energy. Direct observations of the Cornubian batholith, in outcrop and mines, have generally been within a vertical elevation range of ± 600 m OD. However, the Carnmenellis Granite has been proved to a depth of just over 900 m below surface (-800 m OD) in the deepest mines (Dolcoath and South Crofty) and to a depth of 2600 m below surface (-2400 m OD) in the Rosemanowes boreholes. Knowledge of the subsurface geometry and extent of the larger part of the batholith is indirect and entirely dependent upon the interpretation of geophysical data. There is limited information from fossil-fuel exploration due to absence of these resources in the region, although seismic survey information useful for interpreting the deeper structure does occur in the area onshore and offshore of Lyme Regis in the south-east of the region. Other geophysical investigations, including gravity and magnetic surveys, also provide information on the deeper structure.

3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

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

The bedrock geology of the region divides broadly between sedimentary cover rocks in the east and basement rocks in the west (Figure 3). The Mesozoic and Cenozoic sedimentary cover rocks (Figure 3) range in age from 25 to 300 Ma, and include a wide variety of sedimentary rocks, including sandstone, siltstone, mudstone and limestone, interbedded on a metre to 100 m scale. The Palaeozoic basement rocks (broadly 315 to 410 Ma in age) mainly comprise Devonian and Carboniferous, largely sedimentary sequences, deformed and metamorphosed by the effects of the Variscan Orogeny (mountain building) event, which ended about 300 Ma. These rocks, along with rocks of the same age along the southern onshore fringe of south Wales, lie south of the Variscan fold and thrust 'front' (Stephan et al., 2016) — also termed the 'Variscan cleavage front' — and are thus distinct in character from other Devonian and Carboniferous sedimentary rocks across much of Britain, in that they developed significant folding, faulting (often thrusting) and cleavage. The deformed sedimentary rocks of the region are intruded by the major Permian Cornubian granite batholith, known from outcrops forming the moors of the south-west but also potentially connecting at depth (Section 4).


BH72/64
N
ILFRACOMBE
LYNTON
MINEHEAD
BURTON ROW
BRENT KNOLL
PURITON
Lundy
WATCHET
QUANTOCK HILLS
BARNSTAPLE
EXMOOR
BRIDGWATER
BIDEFORD
Hartland Point
Brushford Fault
TAUNTON
WELLINGTON
Sticklepath
Chulmleigh
LINE OF SECTION
ILMINSTER
NE
PETROCKSTOW 1B
Petrockstowe Basin
Petrockstowe
TIVERTON
BLACKDOWN HILLS
CREWKERNE
CHARD
SEABOROUGH 1
HOLSWORTHY
Lustleigh
MARSHWOOD 1
OKEHAMPTON
LYME REGIS
Boscastle
Tintagel
WILSEY DOWN
LAUNCESTON
DEVON GREAT CONSOLS D3
EXETER
BRIDPORT
Camelford
BOVEY TRACEY G 1
SIDMOUTH
Fault
Chudleigh
REDMOOR RM82-29
DARTMOOR NATIONAL PARK
Bovey Basin
74/30
Trevose
PADSTOW
BODMIN MOOR
WADEBRIDGE
TAVISTOCK
NEWTON ABBOT
Callington
Gunnislake
ASHBURTON
BODMIN
TORQUAY
LISKEARD
TOTNES
PLYMOUTH
Paignton
Perranporth
LINE OF SECTION
IVYBRIDGE
Brixham
St Agnes
St Austell
DARTMOUTH
RADNOR 16 ST AGNES
St Ives
Mevagissey
REDRUTH
CM.1 CAMBORNE
CORNISH LAND VENTURES 10
SW
PENZANCE
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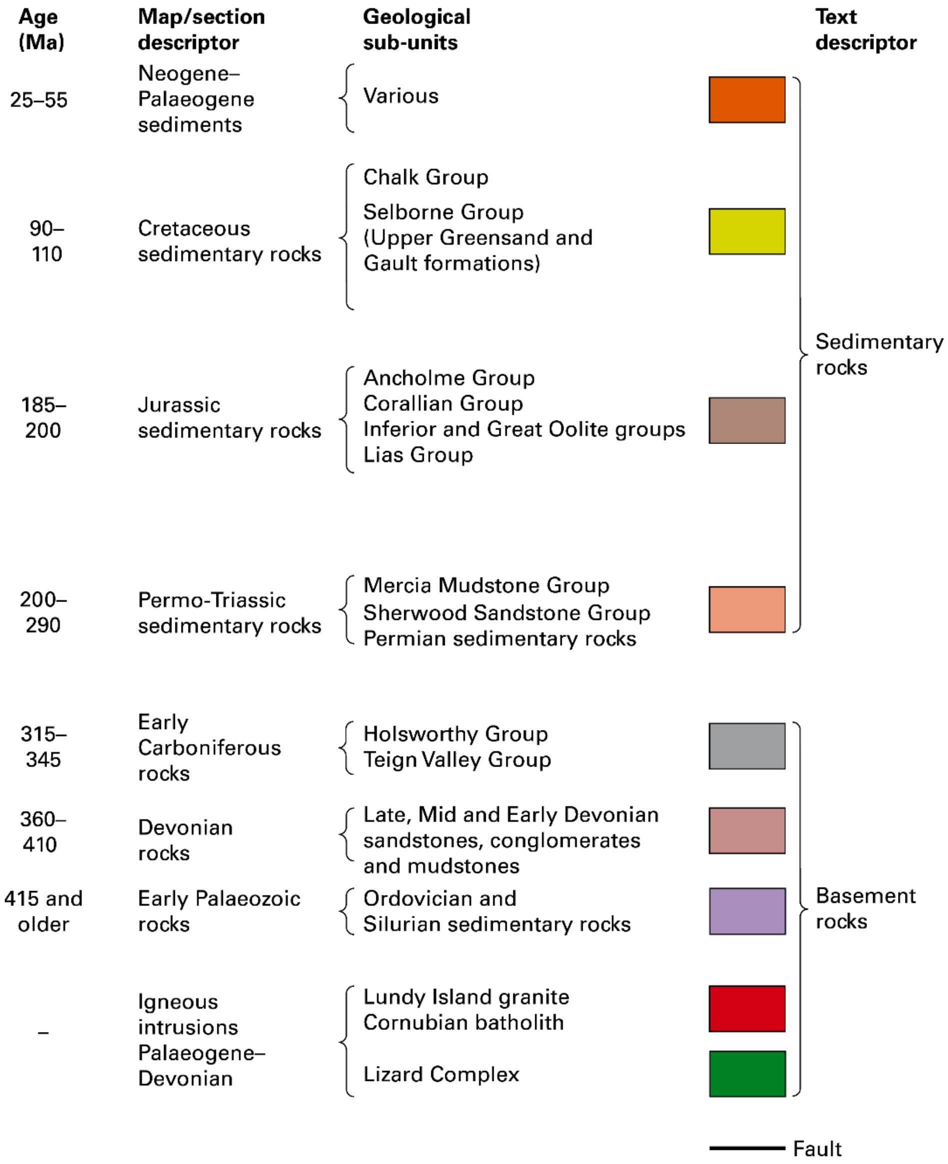

Figure 3 Generalised geological map and key showing the distribution of sedimentary rocks and basement rocks in the onshore South-west England region. The inset map shows the extent of the region in the UK. See Figures 4 and 5 for schematic cross-sections. The 'Geological sub units' column is highly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

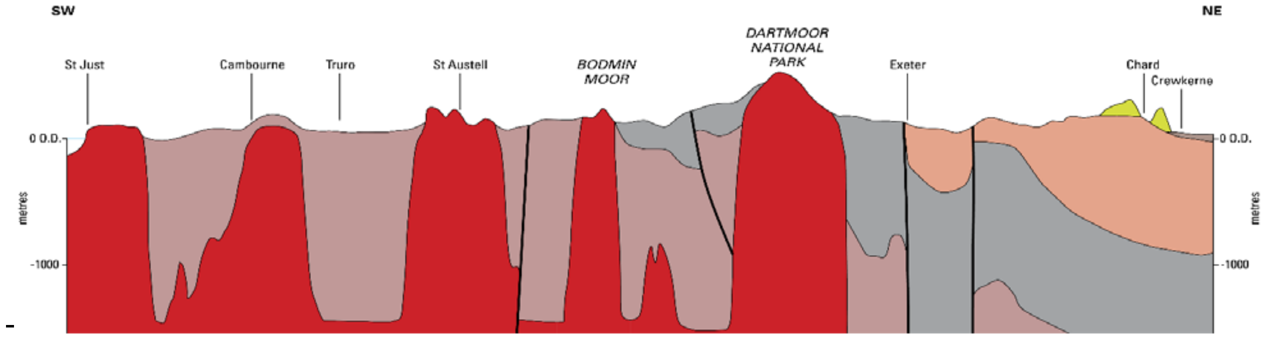

Figure 4 Schematic south-west cross-section from St Just to Crewkerne through the South-west England region. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018

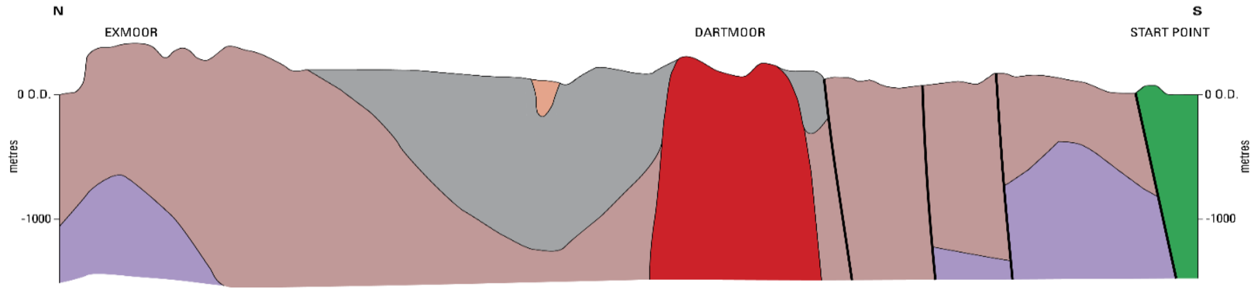

Figure 5 Schematic north–south cross-section through the South-west England region from Exmoor to Start Point. Line of the section and key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI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

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 SOUTH-WEST ENGLAND REGION

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

For the South-west England region, the GVS (Table 3) groups the rocks into two age ranges: sedimentary cover rock (Palaeogene to Permian) and basement rocks comprising Carboniferous and older sediments and igneous intrusions from Palaeogene to Devonian age). The basement rocks incudes 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 sedimentary rocks and as well as higher strength rock (HSR) PRTIs predominantly in the basement rocks.

The GVS for the South-west England region (Table 3) divides rock units into two broad lithostratigraphical systems: Palaeozoic basement rocks and igneous intrusions, mainly comprised of deformed and metamorphosed Carboniferous and older sediments and intruded by the Cornubian granite batholith; and a younger Permian to Palaeogene sedimentary cover.

Numerous potential LSSRs have not been included for a number of different reasons:

- The Bracklesham and Barton groups have not been included as PRTIs due to their insufficient volume.
- The Gault and Upper Greensand formations occur only in the east of the region, capping the Black Down Hills in the area between Exeter and Crewkerne. These strata lie unconformably on the Lias Group in the east and the Mercia Mudstone Group in the west of the Black Down Hills area. These rocks do not descend into the depth range of interest in the onshore part of the region and are not discussed further.
- Similarly, the undivided Kellaways and Oxford Clay formations and the Great Oolite Group only crop out to the east of Crewkerne, in the extreme eastern part (Great Oolite Group) or just outside (Kellaways and Oxford Clay formations) the region. They do not extend to the depth range of interest within the region and are therefore not discussed further in this report.
- The unnamed mafic Palaeogene igneous intrusion (HSR) is inferred at depth beneath the Lundy Island granite . It occurs below the depth range of interest and is therefore not discussed further here.
- The Carboniferous Holsworthy Group is not identified as a PRTI on the basis of the significant number of turbiditic sandstones that occur throughout the sequence.

The PRTIs are described in Table 3 in stratigraphical order from youngest to oldest (i.e. in downward succession), grouped by the sedimentary cover rocks and basement rocks. The descriptions include the distribution of the PRTI at surface (outcrop) and where the PRTI is present below the surface (subcrop) within the depth range of interest, along with key evidence for the interpretations. The main geological properties of the PRTIs and how these vary across the region are also summarised. Data are mostly taken from the BGS Regional Guide to South-west England (Edmonds et al., 1975) and other published sources (see references). They may include terminology or nomenclature that has been updated since those publications were released. The term ‘mudstone’ follows BGS usage to include claystone and siltstone-grade siliciclastics (Hallsworth and Knox, 1999). The locations of boreholes referred to in this chapter are shown on Figure 3.

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

Maps showing the regional distribution of PRTIs between 200 and 1000 m below NGS datum for the three generic host rock types are provided in Figures 6, 7 and 8. A summary map showing the combined lateral extent of all PRTIs is provided in Figure 9.

Table 3 Schematic GVS for the South-west England 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	
SEDIMENTARY COVER ROCKS	Neogene to Palaeocene	Oligocene (undivided) (including Eocene to Miocene)	Varied	N/A	Undivided formations offshore and onshore in Petrockstowe and Bovey basins	N/A	N/A
		Bracklesham and Barton groups (undivided)	Sand, silt and clay	N/A	N/A	N/A	N/A
		Eocene to Miocene rocks (undivided)	Clay, silt, sand and gravel	N/A	N/A	N/A	N/A
		Unnamed igneous intrusion, Palaeogene (basement rocks—placed here due to age)	Felsic rock	Lundy Island granite	N/A	N/A	N/A
	Cretaceous	Chalk Group	Chalk	N/A	N/A	N/A	Chalk Group (not significant)
		Upper Greensand and Gault formations (Selborne Group)	Mudstone, sandstone and limestone	N/A	N/A	N/A	Upper Greensand Formation (not significant)
		Lower Cretaceous (undivided), offshore only	Varied	N/A	Lower Cretaceous (undivided)	N/A	N/A
	Jurassic	Late Jurassic rocks (undivided)	Mudstone, siltstone and sandstone	N/A	Various Late Jurassic formations	N/A	N/A
		Ancholme Group	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Corallian Group	Limestone, sandstone, siltstone and mudstone	N/A	N/A	N/A	Corallian Group (not significant)
		Great Oolite Group	Mudstone-dominated, and ooidal and bioclastic limestone	N/A	N/A	N/A	Great Oolite Group (not significant)
		Inferior Oolite Group	Limestone, sandstone, siltstone, mudstone and ironstone	N/A	N/A	N/A	Inferior Oolite Group (not significant)
		Mid Jurassic rocks (undivided), offshore only	Mudstone, sandstone and limestone	N/A	Various Mid Jurassic formations	N/A	N/A
		Lias Group	Mudstone with sandstone, limestone and ironstone	N/A	Bridport Sand, Beacon Limestone, Dyrham, Charmouth Mudstone and Blue Lias formations	N/A	N/A
	Triassic	Mercia Mudstone Group (includes Penarth Group as combined with Mercia Mudstone Group in NGS3D)	Dominantly red mudstones and subordinate siltstones, with halite and gypsum beds (Penarth Group—interbedded limestone and mudstone)	N/A	Penarth Group and Blue Anchor, Branscombe Mudstone, Arden Sandstone and Sidmouth Mudstone formations of Mercia Mudstone Group	Somerset Halite Member	N/A
		Sherwood Sandstone Group	Sandstone with conglomerate and mudstone	N/A	N/A	N/A	Helsby Sandstone and Chester Sandstone formations
	Triassic to Permian	Permian and Triassic rocks (undivided)	Mudstone, siltstone and sandstone	N/A	Various Permian and Triassic formations (undivided)	N/A	N/A
	Permian	Permian rocks (undivided)	Mudstone, siltstone, sandstone and conglomerate	N/A	Aylesbeare Mudstone Group	N/A	Dawlish Sandstone Formation (Exeter Group)
BASEMENT ROCKS	Permian	Permian igneous intrusion	Granite	Cornubian batholith	N/A	N/A	N/A
	Carboniferous	Carboniferous Limestone Supergroup	Limestone	N/A	N/A	N/A	Carboniferous Sandstone Supergroup
		Holsworthy Group	Mudstone, sandstone, subordinate siltstone and conglomerate	N/A	N/A	N/A	N/A
		Teign Valley and Tintagel groups	Mudstone, siltstone and sandstone	Multiple formations	N/A	N/A	N/A
	Devonian	Late Devonian rocks (undivided)	Mudstone, siltstone, sandstone and limestone	Multiple formations	N/A	N/A	Late Devonian limestone
		Mid Devonian rocks (undivided)	Mudstone, siltstone, sandstone and limestone	Multiple formations	N/A	N/A	Mid Devonian limestone
		Early Devonian rocks (undivided)	Mudstone, siltstone, and sandstone	Multiple formations	N/A	N/A	N/A
		Unnamed igneous, Devonian	Ultramafic and mafic igneous rock	Part of Lizard Complex	N/A	N/A	N/A
		Devonian rocks (undivided)	Hornblende schist and mica schist	Part of Lizard and Start complexes	N/A	N/A	N/A
		Devonian rocks (undivided)	Varied	Undivided formations offshore	N/A	N/A	N/A
	Devonian to Silurian	Early Palaeozoic rocks (undivided)	Varied	Undivided formations at depth	N/A	N/A	N/A

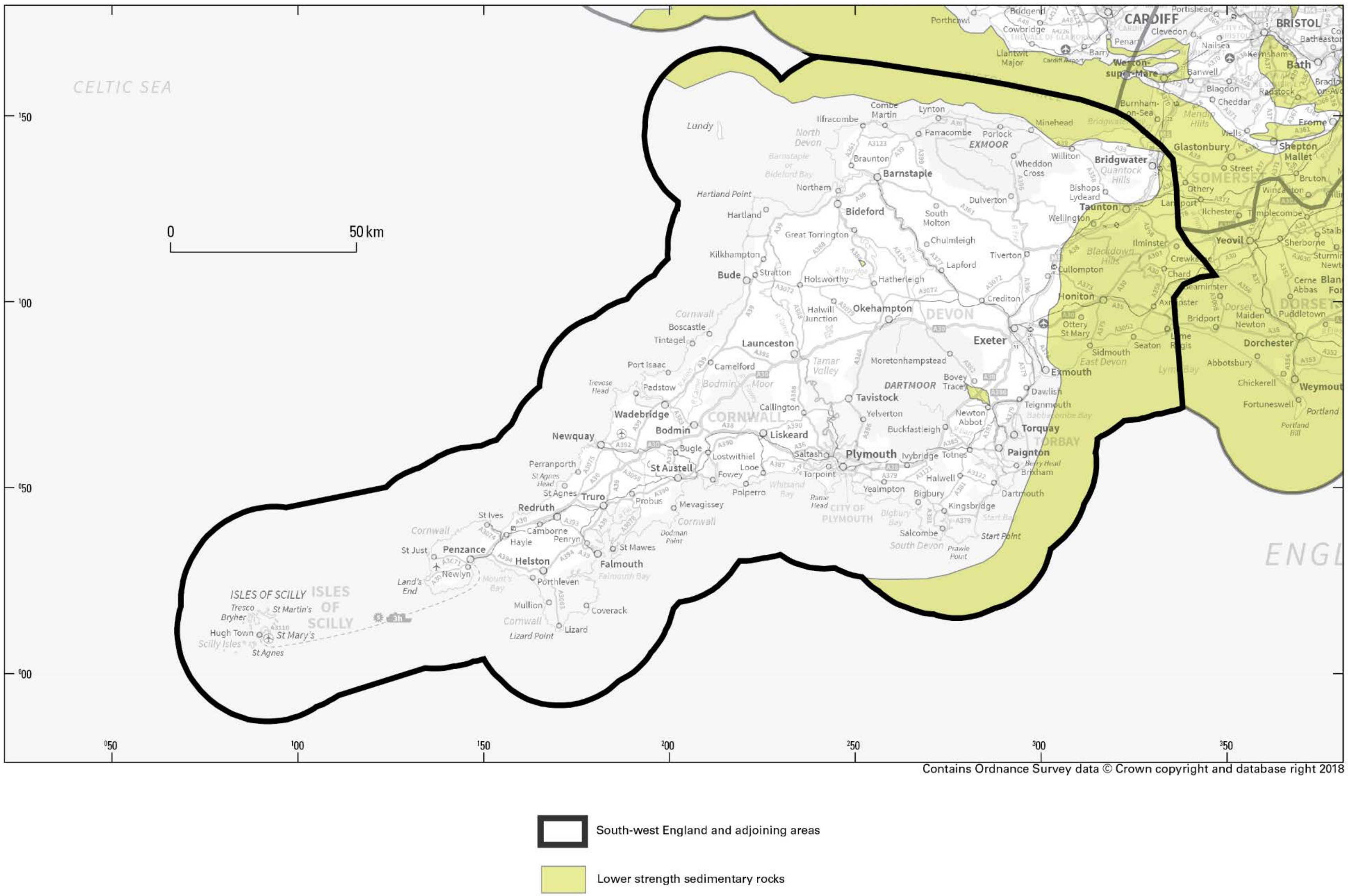

Figure 6 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the South-west England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018

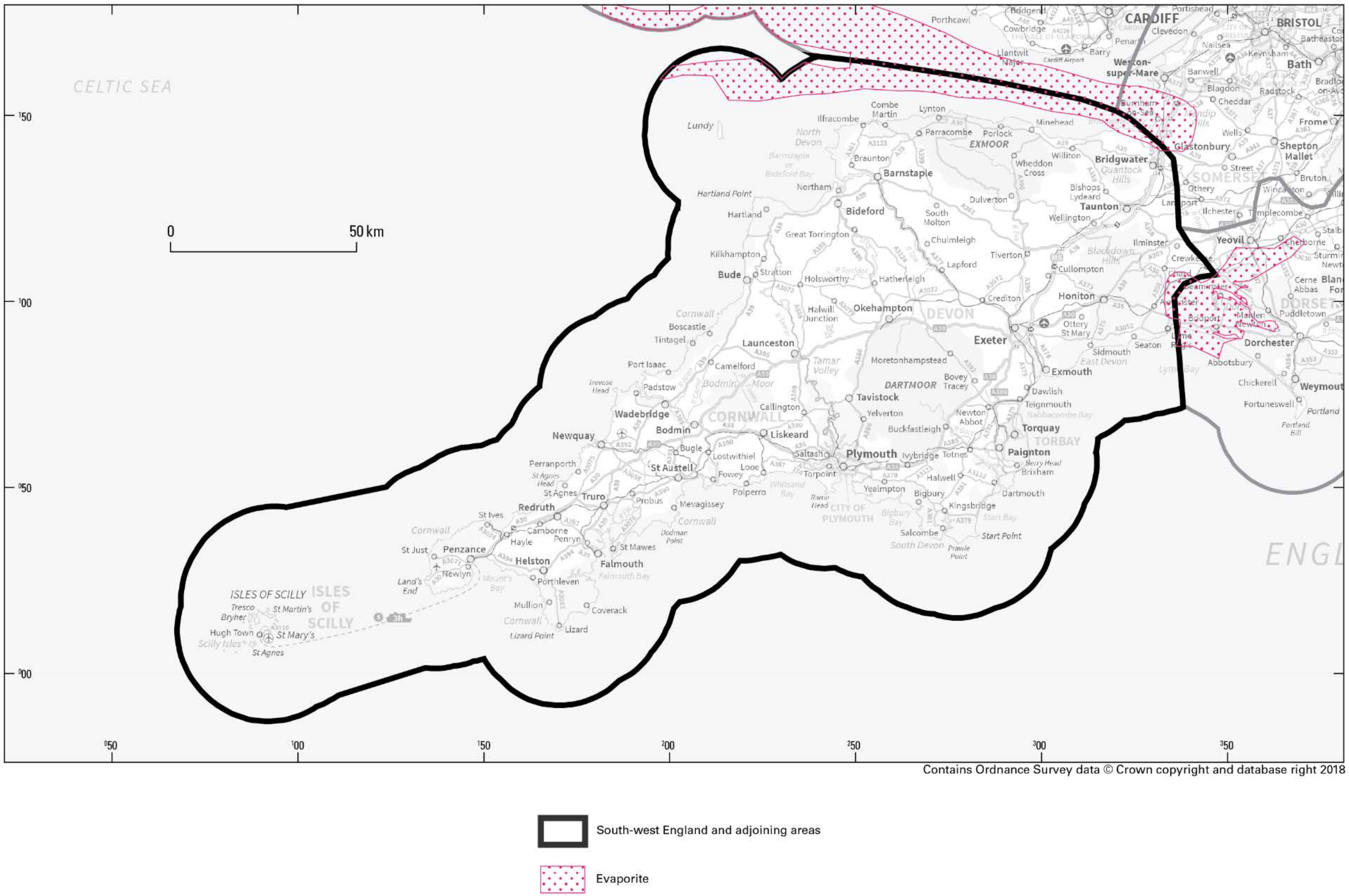

Figure 7 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in the South-west England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018

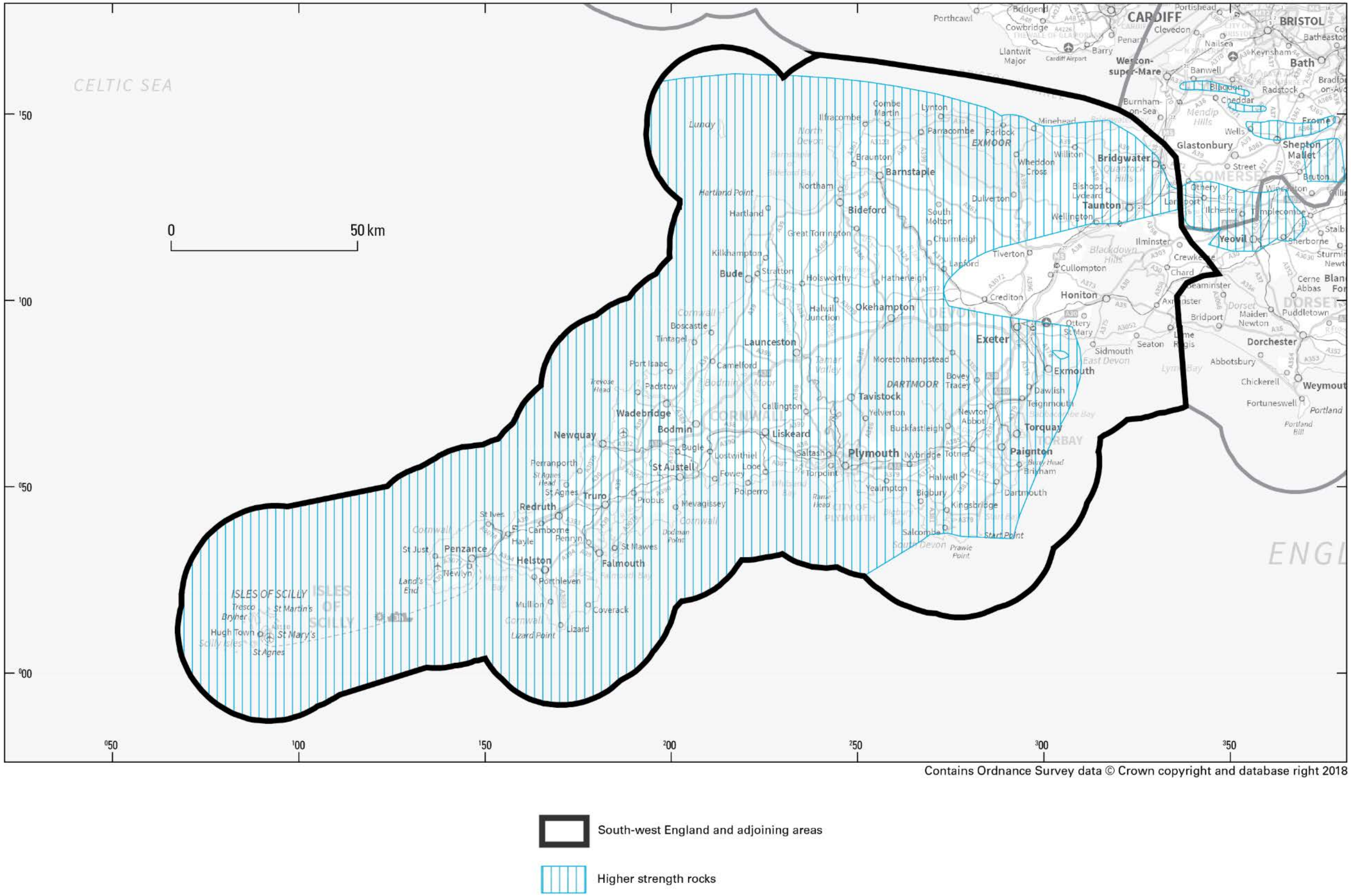

Figure 8 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the South-west England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018

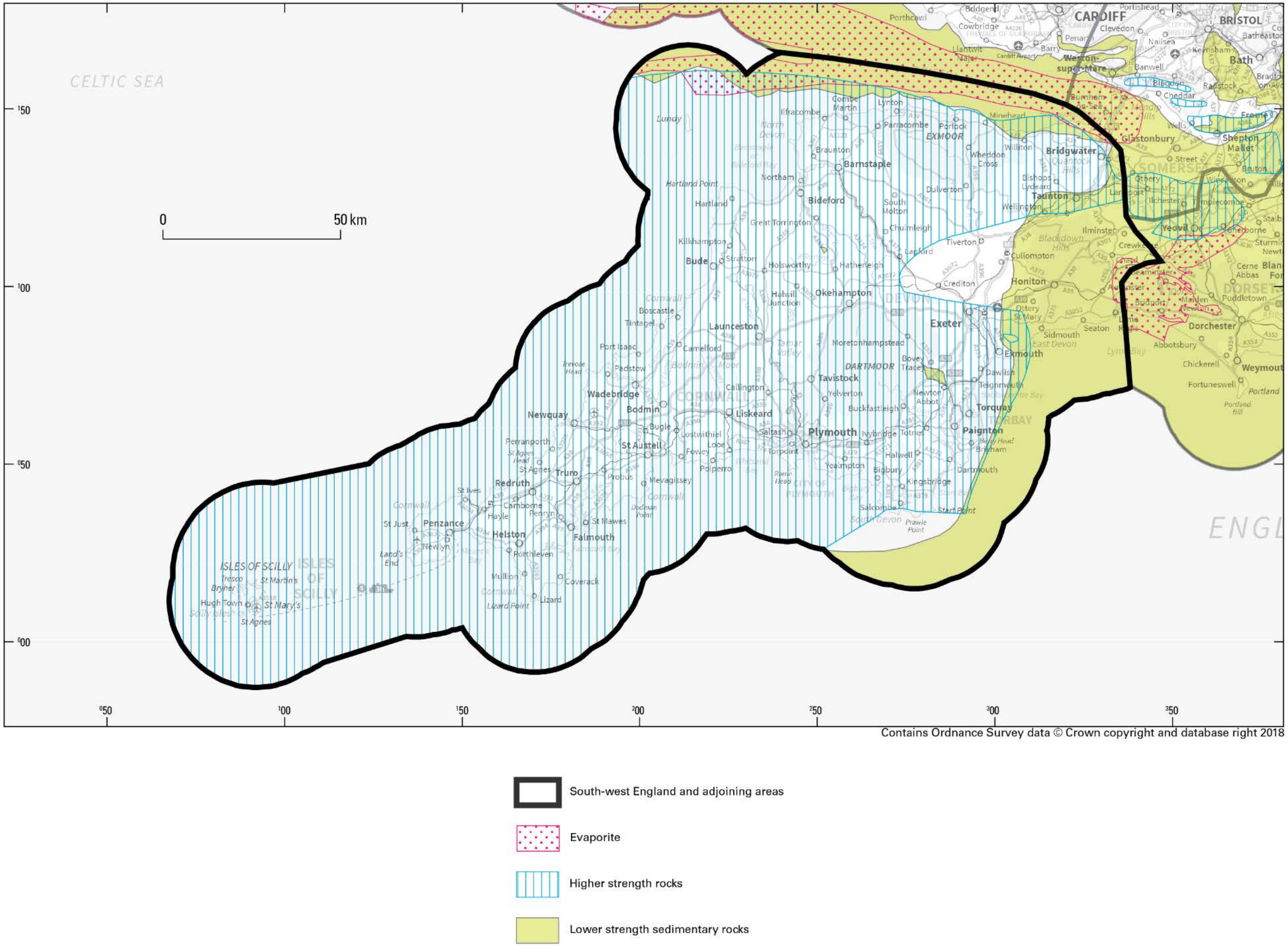

Figure 9 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the South-west England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey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

4.2.1 Sedimentary rocks

Mesozoic and Cenozoic sedimentary cover rocks, which occupy the eastern part of the region, include a number of significant mudstone-dominated formations designated as potential LSSR PRTIs. The Triassic rocks also include an EVAP PRTI.

The following section describes these PRTIs in descending stratigraphical order. Reference can be made to the summary generalised vertical section from Barton et al. (2011) (Figure 10).

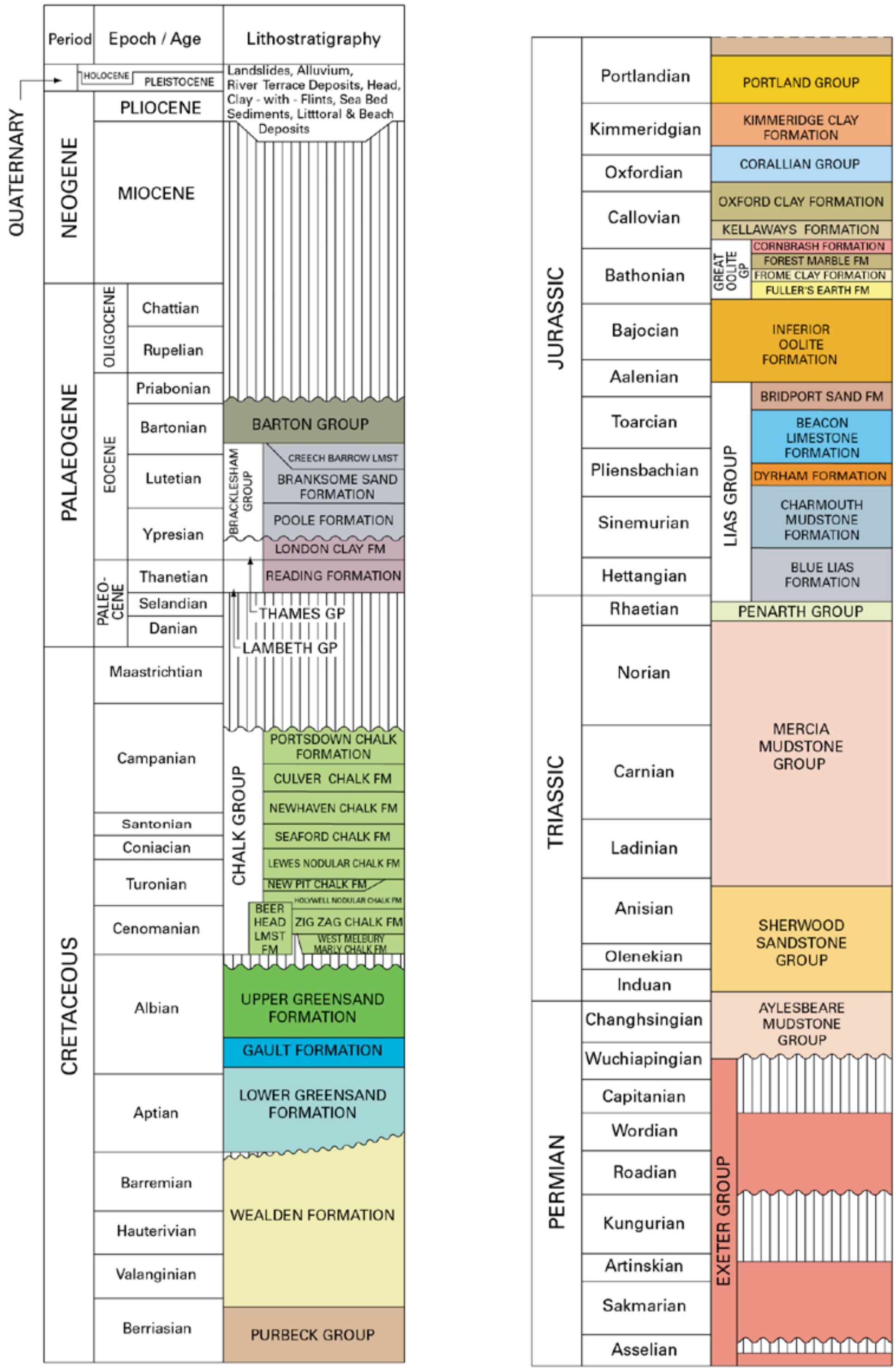

Figure 10 Palaeozoic–Cenozoic stratigraphy in the east Devon–Dorset region (from Barton et al., 2011). Note some of the stratigraphical names have now been superseded (see BGS Lexicon).. British Geological Survey © UKRI 2018

4.2.1.1 UNDIVIDED OLIGOCENE ROCKS — LSSR

The mid Eocene to Oligocene Bovey Formation, comprising clays, sands and lignites, is mostly contained in a series of partly fault-controlled, non-marine sedimentary basins, which formed along the length of the Sticklepath–Lustleigh fault (Figure 11), a major north-west – south-east-trending dextral strike-slip fault (Edmonds et al., 1975; King, 2016). Many of the basins are of insufficient volume to be considered as PRTIs with the exception of the Bovey Basin between Bovey Tracey and Newton Abbot in south Devon and the Petrockstowe Basin in north Devon. Offshore, these rocks occur in the Stanley Bank Basin east of Lundy Island in the Bristol Channel. The basin, 20 km x 30 km and some 20 km north-west of Barnstaple lies on a continuation of the Sticklepath–Lustleigh fault line. Thicknesses are unknown and hence it is not known if these rocks extend into the depth range of interest.

The Petrockstowe Basin, which is 661m deep, contains Bovey Formation sediments that range from cobble gravels to almost sand-free, kaolinite-rich clays. The main part of the Bovey Basin extends for about 11 km between Bovey Tracey in the north-west and Newton Abbot in the south-east and comprises up to 900 m of the Bovey Formation. The middle Bovey Formation is about 200 m thick and includes the main productive ball clay beds (see Section 8).

Principal information sources

Evidence on the lithology and distribution of rocks of this age comes principally from surface mapping including analysis of exposures and shallow borehole information, as published in BGS and other publications. Only one deep borehole exists to prove the entire sequence in one of these isolated depositional basins: the 697 m-deep Petrockstowe 1B borehole. Evidence for the offshore occurrence comes principally from subsurface geophysical interpretations.

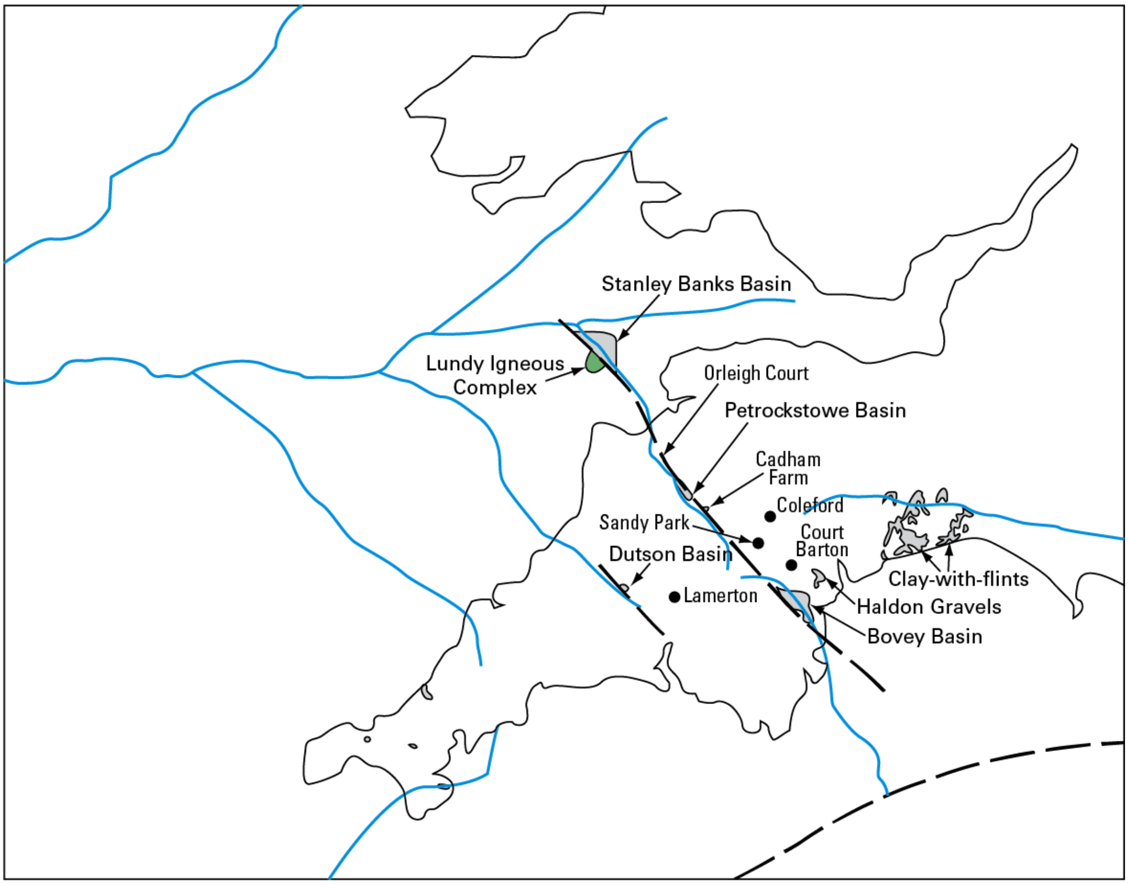

Figure 11 Paleogeography of South-west England during the mid Eocene to Oligocene identifying the basins that formed along the length of the Sticklepath–Lustleigh fault (thick dashed line), a major north-west to south-east-trending dextral strike-slip fault (partly after Murray, 1992) with locations of Tertiary deposits in South-west England.

4.2.1.2 UNDIVIDED EARLY CRETACEOUS ROCKS — LSSR

This classification is used only in the offshore area, grouping together a range of units of Early Cretaceous age. Offshore in the current region, these rocks are represented in outcrops at the seabed in the outer Bristol Channel some 20 km north-west of the Isle of Lundy, and in a discontinuous east–west linear outcrop extending from 10 km south of the Isles of Scilly to 40 km offshore of Plymouth. In the Bristol Channel outcrop, some 20 km by 10 km in extent, the rocks lie within the depth range of interest in the centre of a faulted syncline. Tappin et al. (1994) indicates (using borehole 103/18-1 as evidence; outside the area of interest to the west-north-west of the Isle of Lundy) that the Early Cretaceous in the Bristol Channel comprises dominantly Wealden Formation mudstones (more than 150 m thick) overlain by thin (tens of metres) Lower Greensand Formation, hence not containing significant Gault Formation. South of Cornwall, the rocks dip gently to the south from outcrop and do not reach the depth range of interest even 20 km offshore. Within this outcrop, a representative borehole outside the area of interest to the south (Number BH75/52 (49-005/440)), demonstrates grey-brown, silty mudstones and sandstones to 45 m depth, provisionally interpreted (here) as representing the Early Cretaceous unit.

Principal information sources

Information regarding the lithology and outcrop of these offshore sequences comes partly from a combination of offshore information used to compile the published BGS 1:250 000-scale offshore bedrock mapping. This includes seabed grab samples and shallow cores (spaced about 5 km apart across much of the seabed in the south-west) and limited borehole information. For example, about seven boreholes intersect the Bristol Channel outcrop, and only three intersect the English Channel outcrop. Borehole evidence (namely borehole 103/18-1) provided by Tappin et al. (1994) is also used. The seabed mapping is supported by extrapolation from subsurface seismic interpretations (made by the BGS in support of regional seabed and subsurface mapping), which are also used to provide information on the subsurface thicknesses and structure of the bedrock units.

4.2.1.3 UNDIVIDED LATE JURASSIC ROCKS — LSSR

This classification is applied only in the offshore area, and used only for occurrences in the central outer Bristol Channel. Here, these rocks occur in a faulted syncline, unconformably overlain by Early Cretaceous rocks; they descend through the centre of the syncline into the depth range of interest and have an estimated thickness in NGS3D of several hundred metres.

Borehole information is very limited, with only a small number of shallow boreholes providing useful bedrock information. For example, one borehole within the outcrop demonstrates grey, laminated calcareous mudstone interpreted as Late Jurassic.

Principal information sources

Information regarding the lithology and outcrop of these offshore sequences comes exclusively from a combination of offshore information used to compile the published BGS 1:250 000-scale offshore bedrock mapping. This includes seabed grab samples and shallow cores (spaced about 5 km apart across much of the seabed in the south-west) and limited borehole information. The seabed mapping is supported by extrapolation from subsurface seismic interpretations (made by the BGS in support of regional seabed and subsurface mapping), which are also used to provide information on the subsurface thicknesses and structure of the bedrock units.

4.2.1.4 UNDIVIDED MID JURASSIC ROCKS — LSSR

As with the undivided Late Jurassic rocks classification, this classification is applied only in the offshore area, and used only for occurrences in the central outer Bristol Channel. Here, the rocks descend through the centre of a faulted syncline into the depth range of interest and have an estimated thickness in NGS3D of several hundred metres.

Borehole information is very limited, with only a small number of shallow boreholes providing useful bedrock information. For example, one borehole (Number BH 75/16 (51-005/552)) within the outcrop demonstrates green-grey mudstone to 13.1 m depth.

Principal information sources

Information regarding the lithology and outcrop of these offshore sequences comes exclusively from a combination of offshore information used to compile the published BGS 1:250 000-scale offshore bedrock mapping. This includes seabed grab samples and shallow cores (spaced about 5 km apart across much of the seabed in the south-west) and limited borehole information. The seabed mapping is supported by extrapolation from subsurface seismic interpretations (made by the BGS in support of regional seabed and subsurface mapping), which are also used to provide information on the subsurface thicknesses and structure of the bedrock units.

4.2.1.5 LIAS GROUP — LSSR

The Lias Group crops out in the east of the South-west England region, in the area between Ilminster, Crewkerne and south towards the coast at Lyme Regis. The group is progressively overstepped and cut out from east to west by the Aptian unconformity at the base of the overlying Cretaceous rocks. The group dips gently to the east and the base of the unit only exceeds the depth range of interest in the extreme east of the region, principally in the area 10 km to the north and south of Crewkerne.

The base of the Lias Group occurs at 466 m bgl in the Seaborough 1 borehole (Figure 3) just to the south of Crewkerne. Rocks of Early Jurassic age also occur extensively in the Bristol Channel, and occur within the area and depth range of interest in the central area as far as west as north of the Isle of Lundy. The onshore extension of these deposits outcrops in the area around Watchet and to the west along the Somerset coast within the area of interest.

Rock type descriptions

The Lias Group in this area is represented (in descending stratigraphical order) principally by the Bridport Sand, Beacon Limestone, Dyrham, Charmouth Mudstone and Blue Lias formations, which overall comprise a mudstone-dominated sequence, but with significant vertical variations in sand content and occurrence of limestone beds; these variations are used to define the formations. Coupled with the estimated thicknesses for the formations, it is likely that only the Dyrham, Charnmouth and Blue Lias formations reach the depth range of interest beneath the Crewkerne area.

The principal lithologies of the Bridport Sand Formation in the current study area are rhythmic alternations of siltstone and fine-grained sandstone, with cemented beds (or ‘doggers’) of calcareous sandstone (Barton et al., 2011). A unit of variably sandy mudstone (the Down Cliff Clay Member) occurs at the base. The formation averages 135 m thick in south Dorset, compared to 186.7 m thickness proved in the Winterborne Kingston borehole [384700,097900], some 50 km further east into the Wessex basin, outside the region (Barton et al., 2011), which also demonstrates 80 m thickness for the Down Cliff Clay Member. The formation is thinner where seen in coastal sections in south Dorset; for example, Wilson et al. (1958) describes a thickness range of 47–92 m in the Bridport area.

In the region, the Bridport Sand Formation rest on the Beacon Limestone Formation. This comprises ooidal limestones that reach only several metres thick.

The upper part of the Dyrham Formation comprises poorly cemented, fine-grained sandstone, which includes occasional large argillaceous, silty or sandy limestone nodules (Down Cliff Sand Member and Thorncombe Sand Member; Barton et al., 2011), while its lower part comprises pale to dark grey and greenish grey, micaceous mudstone and sandy mudstone, with interbeds of siltstone or very fine sandstone, in some cases muddy or silty (Eype Clay Member). The formation is well exposed on the south Dorset coast, just outside the eastern extent of the region, where it is around 115 m thick, but it varies in thickness towards the east into the Wessex basin (Figure 12) (Barton et al., 2011; Wilson et al., 1958).

The principal lithologies of the Charmouth Mudstone Formation are dark grey, laminated, fissile mudstone and dark to pale grey and bluish grey mudstones. In addition, the formation contains sporadic concretionary and tabular beds of argillaceous limestone, phosphatic and sideritic nodules, organic-rich fissile mudstone (‘paper shales’), and, in the upper part, silty and sandy beds (Barton et al., 2011). The formation is exposed on the south coast around Lyme Regis where it is about 147 m thick and the Winterborne Kingston borehole proved 127 m; it thickens to over 200 m to the east into the centre of Wessex basin (Figure 12) (the latter two are to the east in the adjacent Hampshire Basin and adjacent arears region).

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. The formation is exposed on the south coast in the current region in the area around Lyme Regis, where it is about 30 m thick. It thickens eastwards into the Wessex basin (Figure 12), reaching more than 200 m thick in the Winterborne Kingston borehole.

Principal information sources

Evidence regarding the lithology and outcrop of the Lias Group in the South-west England region comes principally from surface geological mapping, including from numerous exposures and quarries that are more common in the limestone-dominated facies. The mudstone-dominated units are generally less well exposed, often underlying low or gently sloping ground.

Several deeper boreholes, on the eastern edge of the current region or immediately to the east in the adjacent Hampshire Basin region, also provide useful information. For example:

- the Marshwood 1 borehole (Figure 3) proves 125 m of Lias Group rocks overlying Triassic rocks
- the Seaborough 1 borehole (Figure 3) proves the full thickness of Lias Group (some 447 m) beneath Inferior Oolite Group and overlying Triassic rocks
- the Winterborne Kingston borehole, 50 km outside the region to the east; this provides a useful comparison to the sequence in the Wessex basin

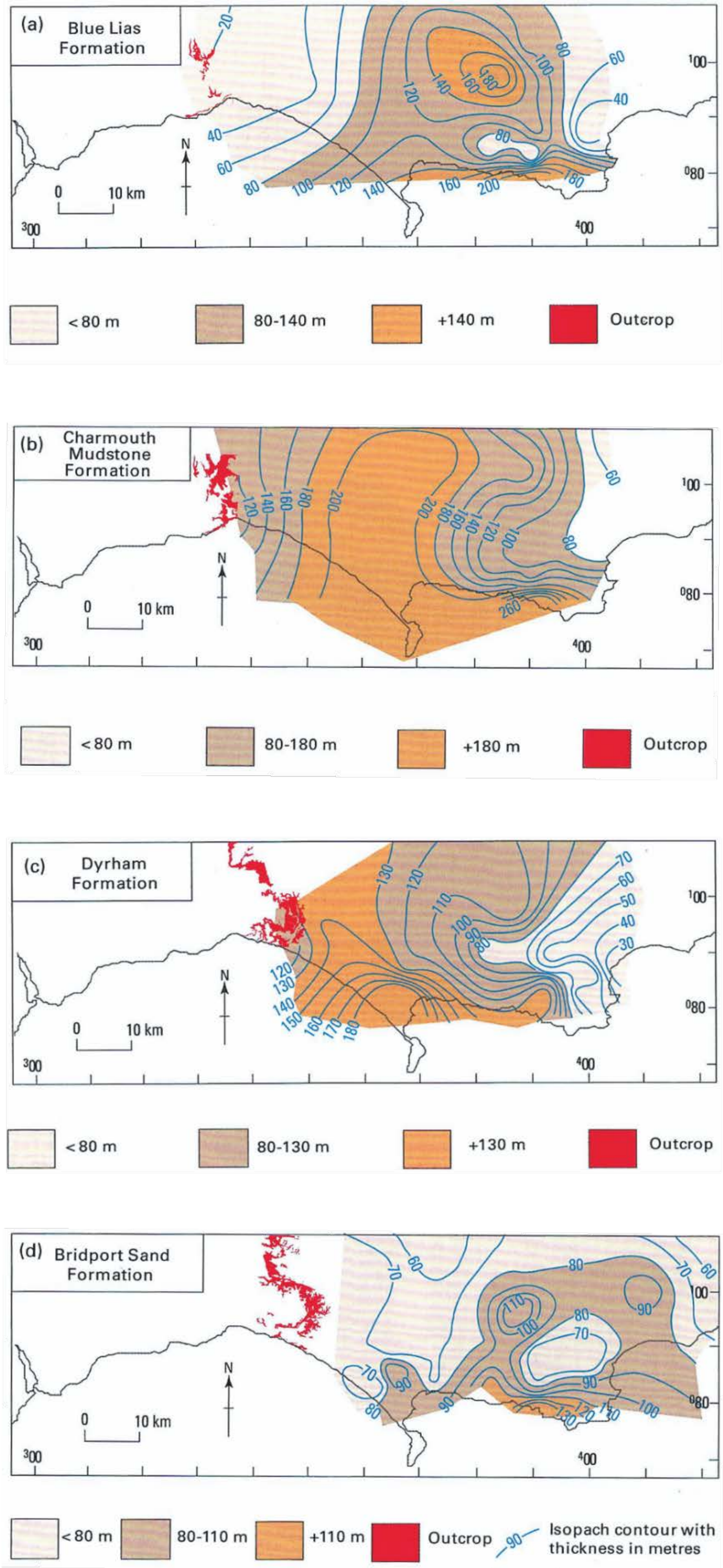

Figure 12 Isopachtye maps for Early Jurassic (Lias Group) formations in Dorset and south-east Devon (from Barton et al., 2011) showing the group dipping gently to the east into the adjacent Hampshire Basin and adjacent areas region, with the base of the unit only exceeding the depth range of interest in the extreme east. British Geological Survey © UKRI 2018

4.2.1.6 MERCIA MUDSTONE GROUP AND THE PENARTH GROUP UNDIVIDED (INCORPORATING THE SOMERSET HALITE MEMBER: LSSR AND EVAP

The Triassic-aged Mercia Mudstone Group crops out in a broad 20 km-wide swathe across the east of the region, from the north Somerset coast across to the east Devon coast, where it is exposed discontinuously between Sidmouth and near Lyme Regis. It rests unconformably on the Sherwood Sandstone Group and is succeeded by the Penarth Group. It dips gently to the east towards the Wessex basin and occurs extensively within the depth range of interest to the east of a line extending from Sidmouth on the south coast, through west of Taunton to west of Watchet on the north coast.

Rock type descriptions

The Mercia Mudstone Group was deposited in a continental terrestrial setting with considerable local relief, under arid or semi-arid conditions. It is composed mainly of red and, less commonly, green and grey mudstone and siltstone, with some localised sandstone units and breccias. Substantial deposits of halite occur in the thicker, basinal successions in central Somerset, but die out on the eastern margin of the South-west England region against a line extending northwards from Bridport through Crewkerne. A significant part of the Mercia Mudstone Group section (over several hundred metres thick and within the depth range of interest) in the central Bristol Channel region is possibly dominated by evaporites (Tappin et al., 1994) representing the westward extension of the Somerset Halite Member seen around Bridgwater. There is, however, only limited information from two locations, onshore to the east of the Bristol Channel (Burton Row borehole; Figure 3) and in the west, south of the tip of Pembrokeshire (borehole 103/18-1, outside of the region). The presence of continuous evaporites in the centre of the Bristol Channel is therefore uncertain. Sulphate deposits (gypsum and anhydrite) and sandstone beds are common at higher stratigraphical levels in the present region, but are a minor constituent throughout most of the group.

Nationally, the group has been divided into several distinct formations, mostly mudstones but with some sandstone units and marginal breccias. These are in descending order: the Blue Anchor Formation; Branscombe Mudstone Formation; Arden Sandstone Formation and the Sidmouth Mudstone Formation (Figure 13). In the present region, on geological maps, the Arden Sandstone Formation has been mapped within an encompassing mudstone unit termed the Dunscombe Mudstone Formation (Gallois, 2001; Barton et al., 2011), but for consistency the national classifications are used here.

The thickness of the Mercia Mudstone Group in the south of the present region is estimated from outcrop as 475 m on the east Devon coast (Barton et al., 2011). Three deep boreholes, which occur on the eastern margin of the South-west England region, also provide thickness information regarding the Mercia Mudstone Group as a whole, and also an indication of whether ‘saliferous’ (halite) beds are present. These are:

- The Puriton Borehole (Figure 3) near Bridgwater, which proves at least 388 m of Mercia Mudstone Group (Stratigraphical Surface Database), extending down from the surface. No halite beds are noted in the log.
- The Seaborough 1 Borehole (Figure 3), 2 km to south-west of Crewkerne, proves 511 m of Mercia Mudstone Group (from 492 to 1003 m depth) but with no significant halite units identified in the log.
- The Marshwood 1 Borehole (Figure 3), 10 km north-west of Bridport, proves 624 m of Mercia Mudstone Group (from 147 to 771 m depth); some 175 m thickness of ‘saliferous beds’ are noted in the log from 352 to 527 m depth.

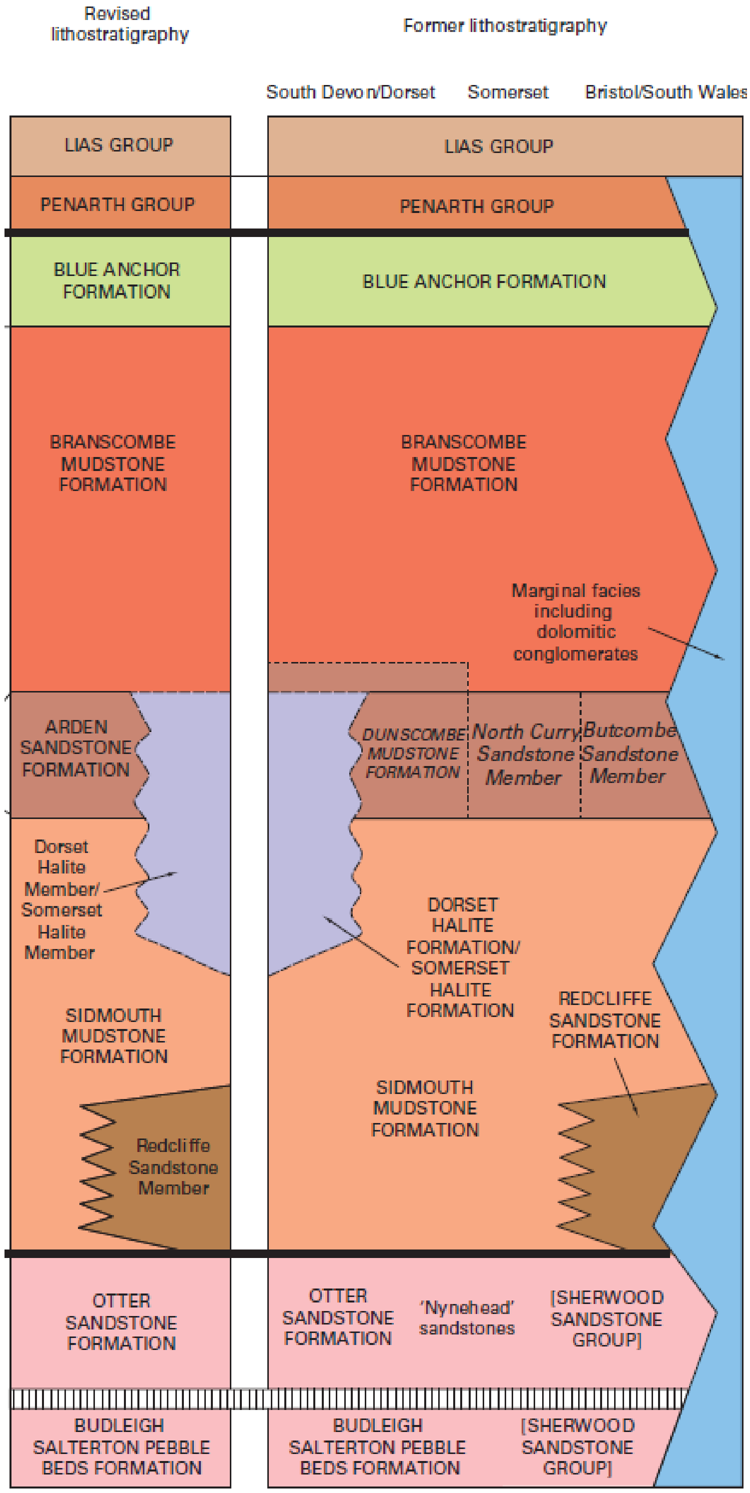

Figure 13 Stratigraphical nomenclature of the Mercia Mudstone Group (top and bottom delineated by thick black lines) comprising the Blue Anchor Formation, Branscombe Mudstone Formation, Arden Sandstone Formation and the Sidmouth Mudstone Formation (from Howard et al., 2008). British Geological Survey © UKRI 2018

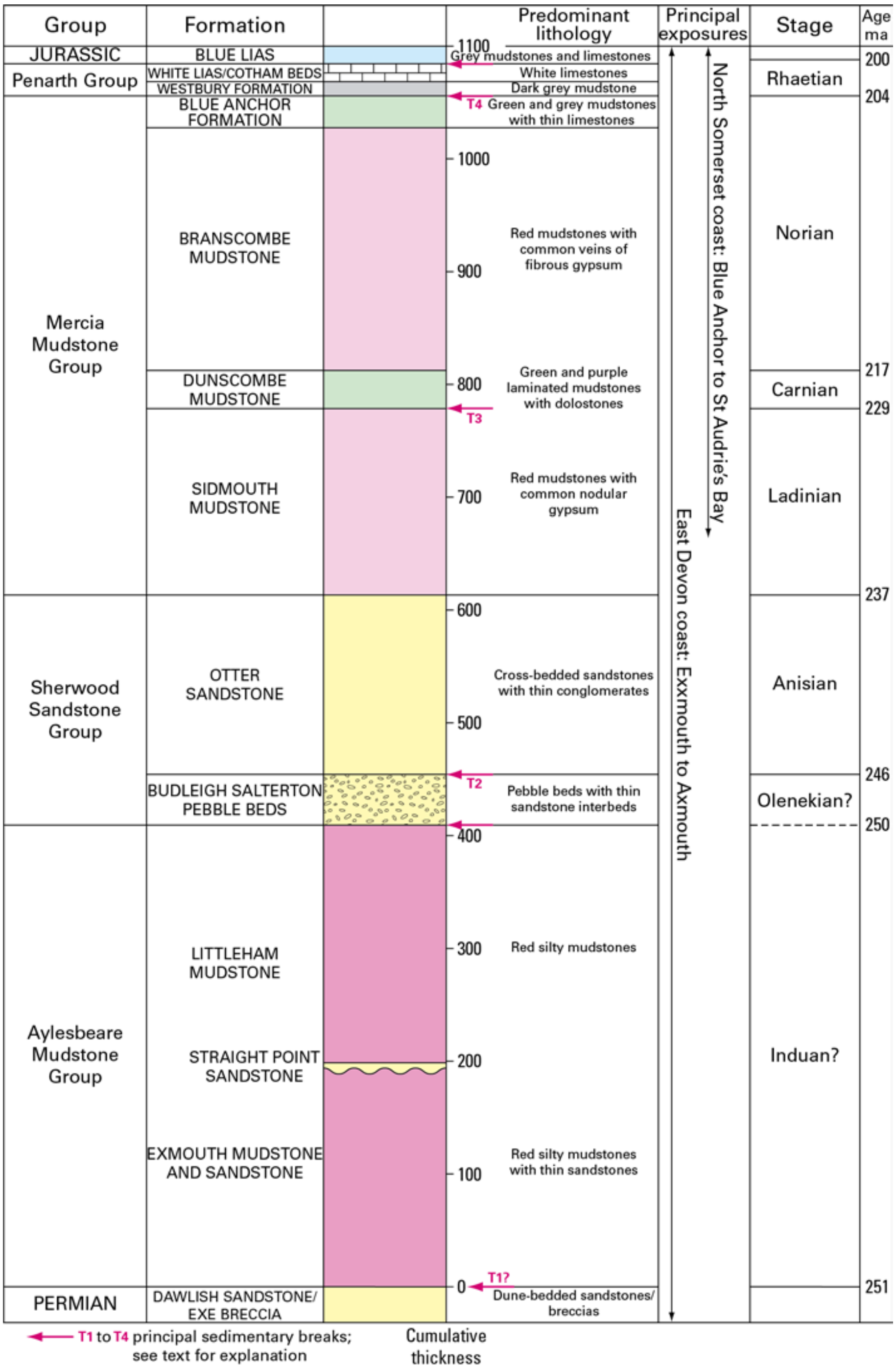

Figure 14 Generalised vertical section for the Triassic rocks of South-west England based on the succession exposed on the east Devon coast. Ages based on Gradstein et al. 2004. See Figure 13 for revised stratigraphic nomenclature. British Geological Survey © UKRI 2018

Barton et al. (2011) uses this information to draw up an isopachyte map of the Mercia Mudstone Group in the east Devon to Dorset region i.e. extending from the east margin of the present region towards the Wessex basin area to the east (Figure 15). This demonstrates a general thinning of the group from a maximum of more than 900 m in the centre of the Wessex basin to about 500 m on the eastern boundary of the present region; an absence of deep boreholes proving the full thickness of the Mercia Mudstone Group means it is not clear if this thinning continues westwards across the present region. Barton et al. (2011) also uses the information to show a western margin to the occurrence of the saliferous/halite beds (Figure 15), which effectively coincides with the eastern margin of the present South-west England region.

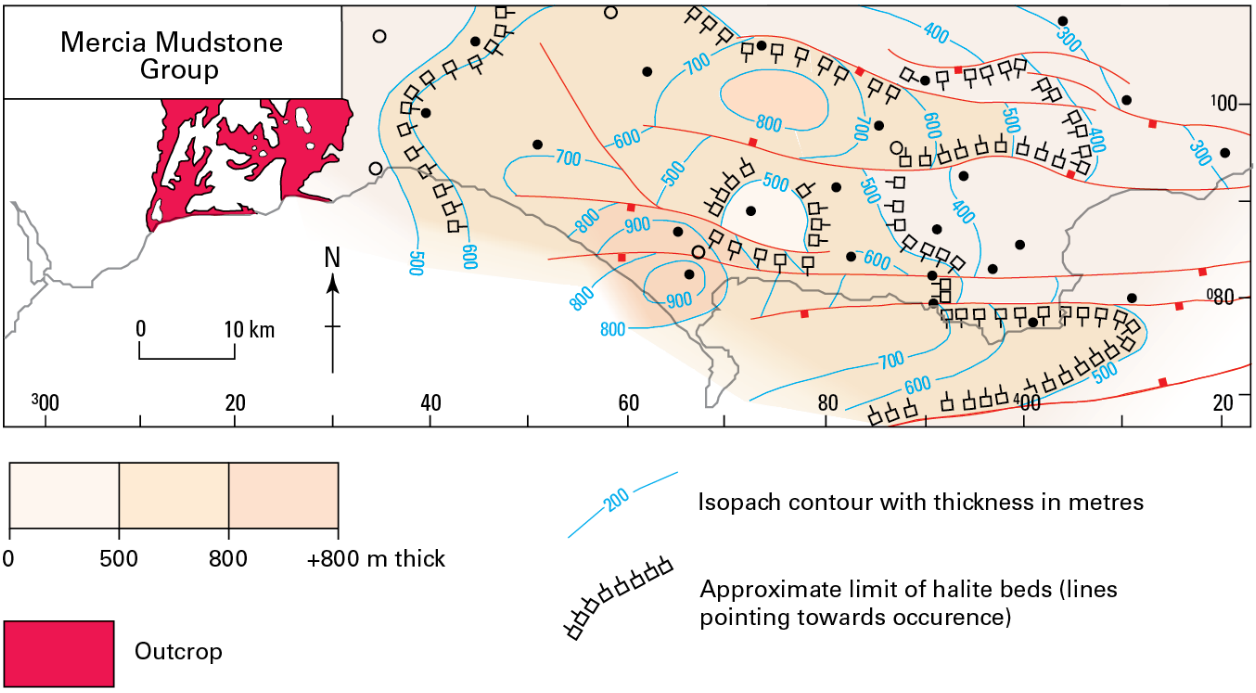

Figure 15 Isopachyte map for the Mercia Mudstone Group in Dorset and south-east Devon (from Barton et al., 2011); lines of box markers show approximate limit of halite beds (lines pointing towards occurrence), which coincide with the eastern margin of the region. British Geological Survey © UKRI 2018

The Penarth Group is present in the extreme east of the region and represents an upwards transition from the underlying Mercia Mudstone Group into the Lias Group. In NGS3D the Mercia Mudstone and Penarth groups are modelled as a combined unit. The Penarth Group, a PRTI, comprises mudstones with subordinate limestones. The unit is best exposed on the west Somerset coast between Watchet and Lilstock. At Blue Anchor the Penarth Group is approximately 20 m in thickness (Edmonds et al., 1975; Tappin et al., 1994). The unit extends offshore into the Bristol Channel. In borehole 103/21-1 the Penarth Group is 32 m thick and comprises interbedded calcareous shale and limestone. In borehole 103/18-1 the Penarth Group is 10 m thick. Both these boreholes are outside the area of interest in the extreme west of the Bristol Channel basin (Tappin et al., 1994).

Rock type descriptions

Lithologically, the Blue Anchor 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, an upper unit of grey, black, green and, rarely, red-brown dolomitic mudstone occurs, with some yellowish-grey dolostones. The Blue Anchor Formation is around 25 m thick on the coast near Lyme Regis, which is consistent with the 7–12 m seen in the Wincanton area to the east; the formation thickens to the east towards south Dorset where 60 m occurs, and thins northwards towards the Mendips (see companion Bristol and Gloucester region report).

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 formation is over 200 m thick in south coast exposures (Barton et al., 2011). The mudstones are mostly structureless, with a blocky weathering habit. Gypsum and anhydrite, locally of economic importance, is common throughout in beds, nodules and veins. In south Devon and Somerset (and extending into Gloucestershire), the highest 10–20 m of the formation include common beds of greenish grey mudstone, giving rise to markedly colour-banded sections where exposed.

Below the Branscombe Mudstone Formation, the Arden Sandstone Formation consists of interbedded mudstone, siltstone and sandstone, predominantly greenish grey in colour. The proportion of sandstone is variable and is locally the dominant lithology. The unit is 24 m thick on the south Devon coast in the east of the South-west England region.

The lowest part of the Mercia Mudstone Group is the Sidmouth Mudstone Formation, which is around 220 m thick in south coastal exposures; it thickens eastwards from the present region. The formation comprises red-brown, mostly structureless, dolomitic mudstone with sporadic, thin beds of siltstone and fine-grained sandstone (more common and thicker — up to 1.2 m — in the lower part); grey-green reduction patches and spots are common in the mudstones.

Principal information sources

Although it often forms low-lying ground, the Mercia Mudstone Group is locally well exposed in the South-west England region, with good exposures occurring on the north Somerset coast at Blue Anchor, and on the south coast around Sidmouth. It gives rise to characteristic red soils, which 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), and Benton et al. (2002). Local details are provided in the 1:50 000 map sheet geological memoirs.

Information regarding the Mercia Mudstone Group is also provided through analysis of a number of deep boreholes within and not far to the east of the South-west England region, including the Puriton, Seaborough 1, Marshwood 1 boreholes in the region (Figure 3) and the Winterborne Kingston and Chickerell 1 (365729, 082219) boreholes outside the region to the east.

4.2.1.7 Undivided Permian and Triassic rocks — LSSR

This classification is used only in the offshore area, principally to the south. In south Cornwall and Devon, the rocks overlie a range of basement rocks largely of Devonian age. Between Torquay and Lyme Regis the classification includes a wide range of units from basal Permian through to uppermost Triassic in age, which extend offshore from the coastline. Towards the end of Carboniferous and into the early Permian, on-going regional scale extension on earlier thrusts and steep faults led to the formation of deposition basins such as the Plymouth Bay basin which filled up with up to 8 km of Permian deposits (Evans, 1990). This in turn led to eustatic uplift and unstable conditions at the crust/mantle boundary conducive to granite generation and magma intrusion at the front of the southerly extending major nappe pile (Figure 16). A southward dip means the base of this undivided sequence extends to below the upper depth range of interest limit in the offshore to the south of Cornwall and Devon (Figure 16). Much of the offshore area of Lyme Bay is underlain within the depth range of interest by this sequence, principally represented by the Mercia Mudstone Group.

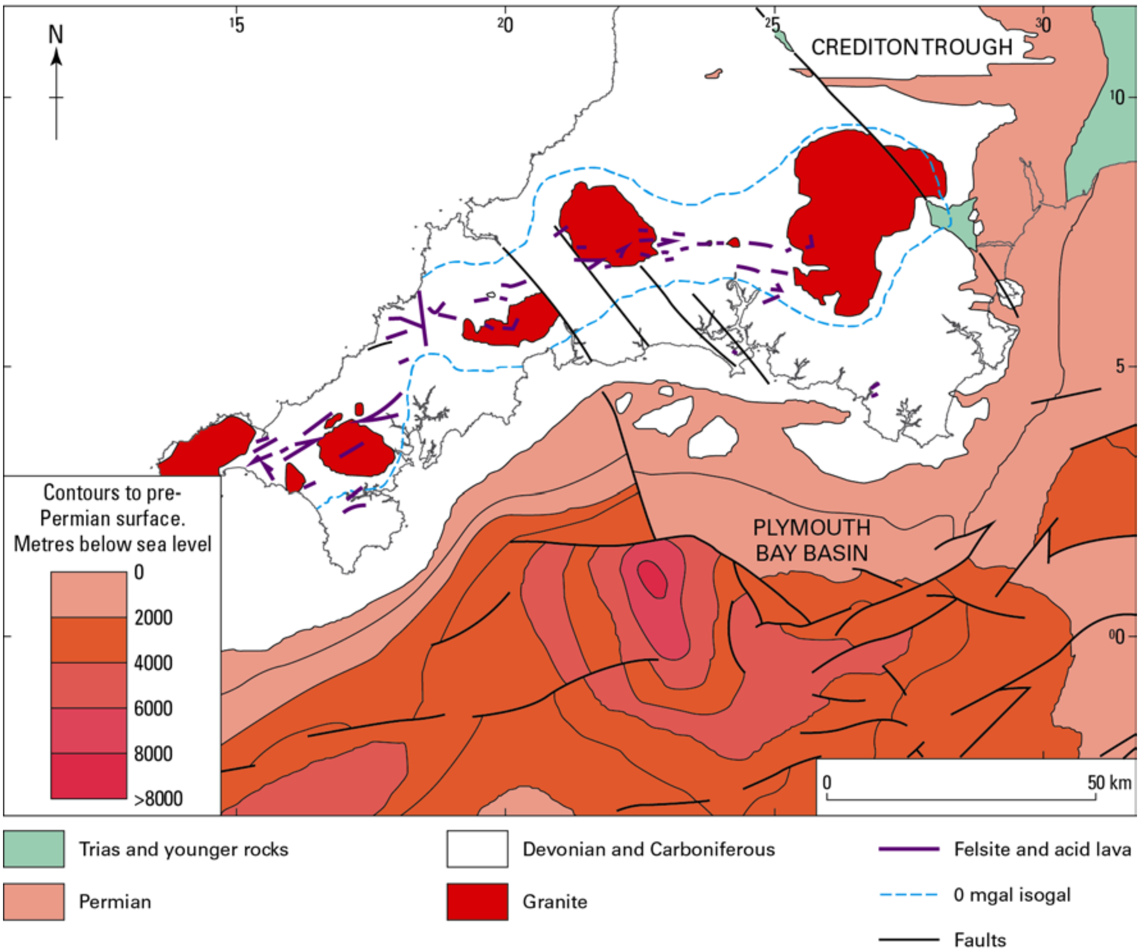

Figure 16 Depositional basins formed during the late Carboniferous to Permian that filled up with up to 8 km of Permian sediments (Evans, 1990). British Geological Survey © UKRI 2018

Principal information sources

Information regarding the lithology and outcrop of these offshore sequences comes exclusively from a combination of offshore information used to compile the published BGS 1:250 000-scale offshore bedrock mapping. This includes seabed grab samples and shallow cores (spaced about 5 km apart across much of the seabed in the south-west) and limited borehole information. The seabed mapping is supported by extrapolation from subsurface seismic interpretations (made by the BGS in support of regional seabed and subsurface mapping), which are also used to provide information on the subsurface thicknesses and structure of the bedrock units.

Rock type descriptions

Borehole information is very limited in the offshore area, with only a small number of relatively shallow boreholes providing useful bedrock information. For example, a borehole (number BH74/30 (50-004/184)) within the Lyme Bay outcrop demonstrates red-brown, gypsiferous mudstones to 17.1 m below the seabed. The offshore outcrop here is, however, continuous with the onshore outcrop, so the lithologies represented will be as described for the Mercia Mudstone Group.

Another potential occurrence is also in Plymouth Bay, where the northern edge of the Plymouth basin is within the 20 km limit. The depth to pre-Permian surface map combined with the subsea surface geology map in Evans (1990), suggests that this interval is within the depth range of interest across Plymouth Bay, but particularly in the east. There is little information with regards to the lithology of the interval. Borehole BH74/41, close to the 20 km offshore limit, recorded a red breccia/conglomerate from 2.2 to 20 m below the seabed, at which depth the borehole terminated.

4.2.1.8 UNDIVIDED PERMIAN ROCKS — LSSR

The PRTI within this classification is represented principally by the Aylesbeare Mudstone Group (previously assigned to the base of the Triassic) (Figure 14), occurring stratigraphically between the sandstone-dominated sequences of the underlying Exeter Group and overlying Sherwood Sandstone Group. The Aylesbeare Mudstone Group crops out in a broad (5 km wide) swathe, running northwards from the coastline near Exmouth, passing just to the west of Wellington, and narrowing to the north as the group thins towards the western side of the Quantock Hills. The group is up to 400 m thick east of Exeter (Edwards and Scrivener, 1999) and 530 m thick on the south coast (Selwood et al., 1984), thinning to between around 50 and 100 m thick to the west of the Quantock Hills (where it is represented by the Littleham Mudstone Formation and underlying Vexford Breccias (Edmonds and Williams, 1985)).

The group dips gently to the east towards the Wessex basin, and hence occurs within the depth range of interest for a broad, approximately 25 km-wide strip as far east as a line passing northwards from Lyme Regis through Ilminster. North and east of the Quantock Hills, the group occurs within the depth range of interest in the Watchet and Bridgwater areas, where it dips northwards away from the Quantocks Hills, reaching below the depth range of interest as it passes into the offshore. For example, in the Burton Row Brent Knoll borehole (Figure 3), rocks (sandstones with subordinate mudstones) correlated with these undivided Permian rocks are encountered at 953 m depth down to the base of the borehole at 1105 m.

Rock type descriptions

Several outliers of the Bussell’s Member, occurring within the Exeter Group beneath the Aylesbeare Mudstone Group, cropping out just north of Exeter, are also classified within the undivided Permian rocks category. This member is only in the order of 25 m thick (BGS Lexicon) and comprises reddish mudstones and fine-grained sandstones. These occurrences are within small (only about 1 km wide) fault-bounded areas within the east–west fault-controlled Crediton trough depositional basin. This unit does not descend into the depth range of interest at any point.

Lithologically the Aylesbeare Mudstone Group is divided locally into two formations: the higher Littleham Mudstone Formation (up to 275 m thick) and the lower Exmouth Mudstone and Sandstone Formation (up to 255 m thick in the Exeter and south coast district). The former is distinguished through the presence of sandstone interbeds (up to 30 m thick in places) within the mudstone-dominated sequence. The Aylesbeare Mudstone Group as a whole is characterised by reddish brown (haematitic) silty mudstones, with the sandstone units being fine to medium-grained and weakly cemented. The proportion of lithologies within the Exmouth Mudstone and Sandstone Formation is 2 per cent claystone, 15 per cent silty claystone, 50 per cent siltstone, 33 per cent sandstone. The Littleham Mudstone Formation is dominated by silty claystone and siltstone with only minor proportions of sandstone (Edwards and Scrivener, 1999).

4.2.2 Basement rocks

Geological description of the Devonian and Carboniferous PRTIs of the South-west England region requires an understanding of their overall depositional and structural characteristics. Although broad correlations are possible in these rocks across the region, their occurrence within a series of variably isolated and fault-bounded depositional basins (Figure 17) (Leveridge and Hartley, 2006), with varying structural controls on deposition and variable subsequent Variscan deformation, means detailed stratigraphical correlations across the south-west based on shared age and lithological characteristics (as is possible with the Mesozoic cover, for instance) are difficult. Figure 18 shows the progressive rifting of the northern passive margin of the Gramscatho Basin, showing the formation of separate basins and associated highs and the northerly then southerly sediment sourcing of the rift basins. Consequently, a complex formational stratigraphy has been developed for the South-west England region to account for these lateral intrabasin and interbasin variations, and these form the basis for the following PRTI descriptions. See section 5.2 for a more overview of the regional tectonic setting of South-west England.

Devonian and Carboniferous rocks across South-west England region within these basins were deformed by the Variscan Orogeny, which produced an intricate series of thrust nappes with complex folding, cleavage development and low-grade metamorphism. Related to this orogeny are major igneous intrusions (not least the regional Permian Cornubian granite batholith) and multiple local-scale intrusions, producing localised thermal metamorphism.

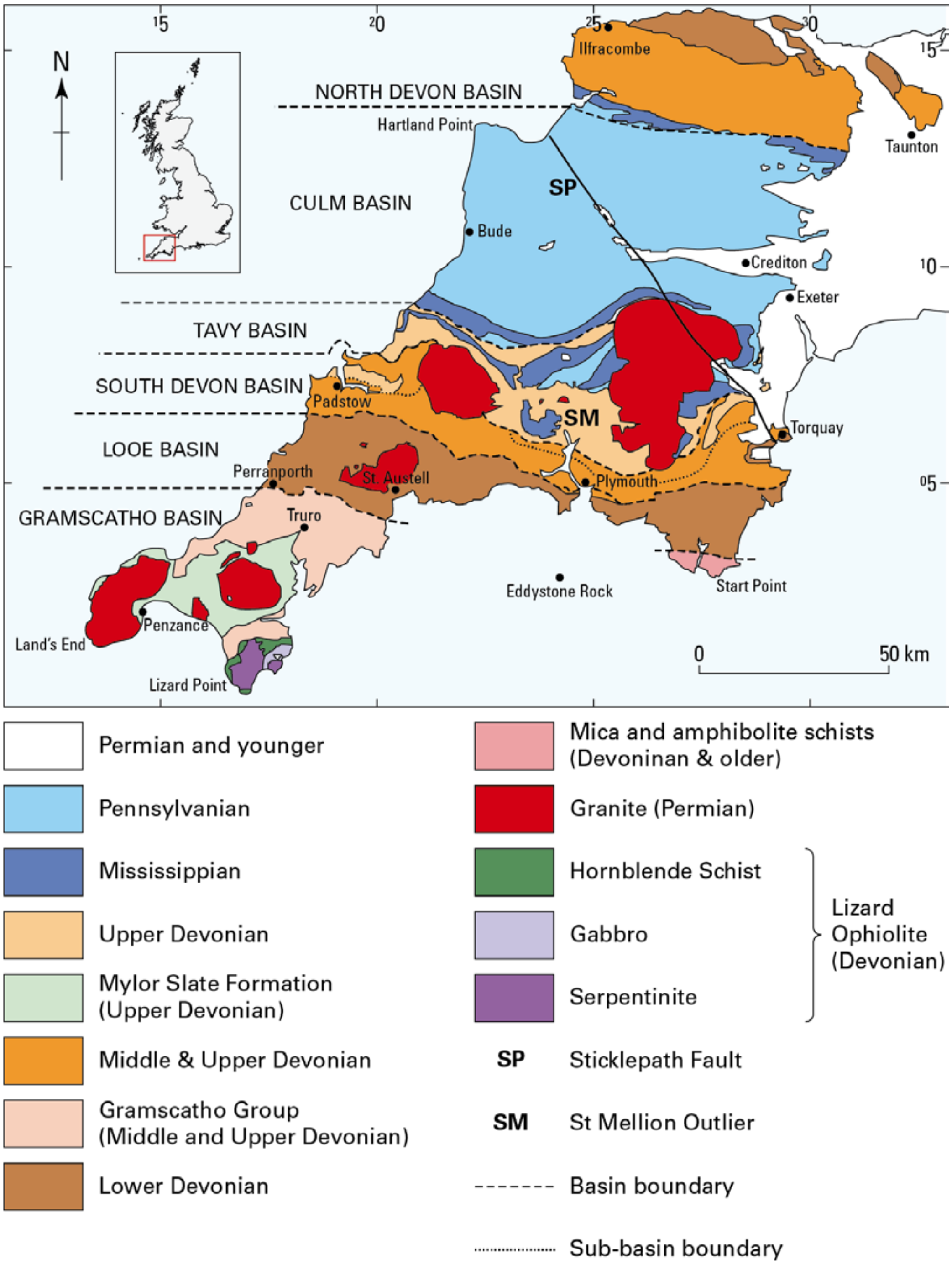

Figure 17 Geology and location of the main sedimentary basins of South-west England. Modified from Leveridge and Hartley, 2006. © Geological Society of London.

The main PRTIs represented in the Devonian and Carboniferous sequences are, therefore, in the HSR category, represented by the more significant 'slaty mudstones' formations of the basinal sequences (Sections 4.2.2.3 to 4.2.2.6). Along with this, there are significant occurrences of HSR PRTIs relating to the intrusive igneous rocks from Palaeogene to Devonian in age (Sections 4.2.2.1 to 4.2.2.2 and 4.2.2.7 to 4.2.2.9). HSR PRTIs are described below in descending stratigraphical order, in agreement with Table 3.

A general lack of useful deep borehole information and subsurface geophysical information means that only a low level of confidence can be placed in the subsurface assessments for Palaeozoic rocks in the region. The few deeper boreholes that do occur do not provide detailed information on the principal stratigraphical boundaries within the Palaeozoic sequences. Thicknesses and depths for concealed formations are generally based on extrapolation from surface outcrops, in particular the well-exposed coastal sections. The confidence in these extrapolations is further reduced owing to the significant structural complexity of these rocks, including complex folding and thrust faulting.

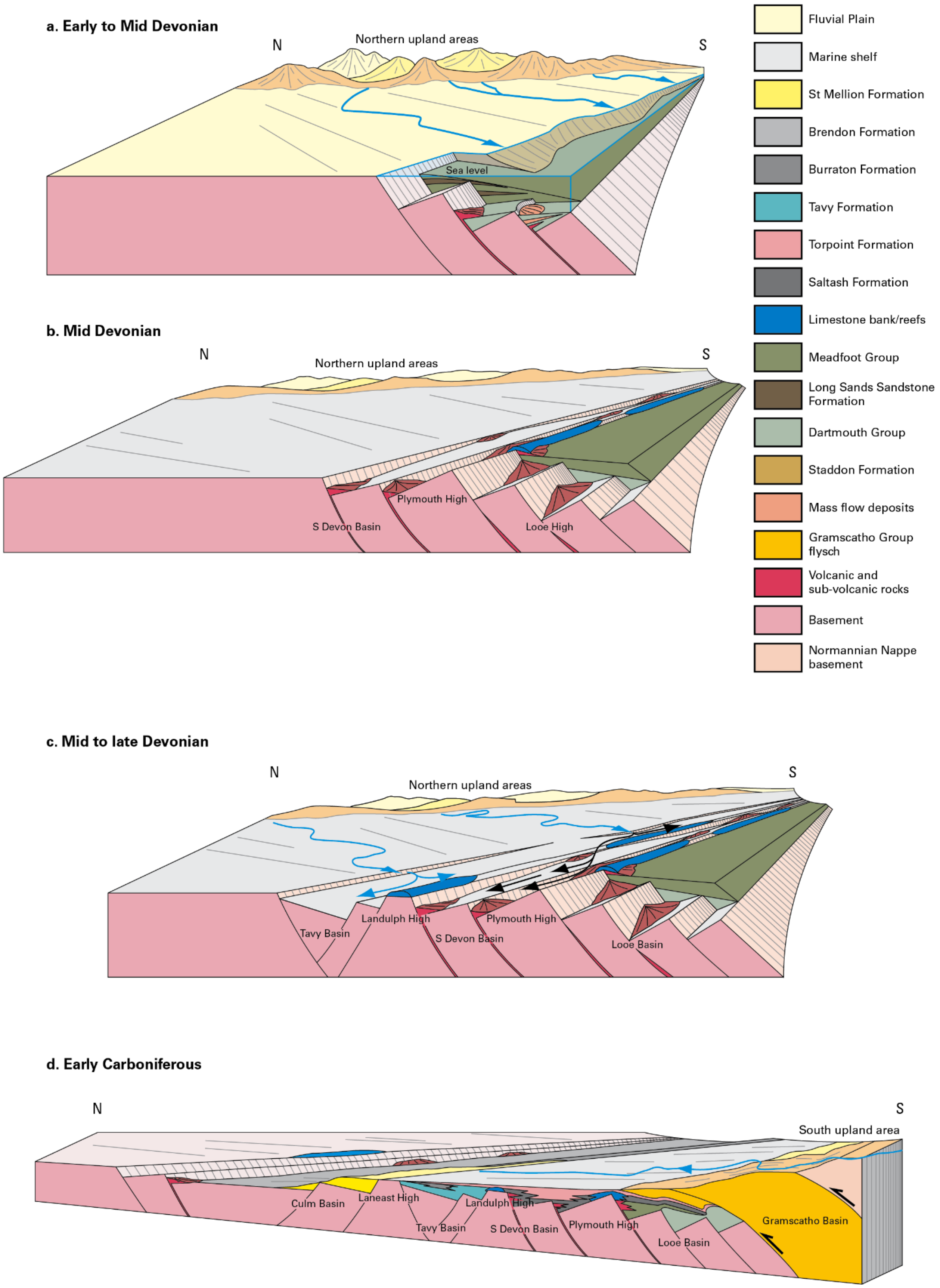

Figure 18 Sequence diagram of the progressive rifting of the northern passive margin of the Gramscatho Basin, showing the formation of separate basins and associated highs and the northerly then southerly sediment sourcing of the rift basins. After Leveridge et al. 2002. British Geological Survey © UKRI 2018

4.2.2.1 UNNAMED PALAEOGENE FELSIC IGNEOUS INTRUSION — HSR

This classification is used in the South-west England region only for the Lundy Island felsic granitic intrusion, which comprises a granite containing 20 per cent alkali feldspar, in a coarse-grained groundmass composed of alkali feldspar, quartz, muscovite and biotite (Thorpe et al., 1990). The intrusion has an approximately 3 x 6 km outcrop on and offshore around the island, and is shown on NGS3D as having steep, faulted sides, and extending down into and through the depth range of interest.

Principal information sources

Information on lithology of the Lundy granite comes from onshore studies on the island, principally coastal exposures (e.g. Thorpe et al., 1990). The extent of the outcrop is as shown on BGS 1:250 000-scale offshore bedrock mapping. Subsurface information comes from BGS subsurface seismic interpretations.

4.2.2.2 PERMIAN GRANITE — HSR

The major granite outcrops of the South-west England region — Dartmoor, Bodmin, St. Austell, Carnmenellis, Land's End and the Isles of Scilly — are traditionally considered as eroded plutons extending upwards from an underlying major Cornubian batholith (Figure 19). The extent of this, identified by a regional negative gravity anomaly, has been inferred to be over 200 km long and 50 km wide (Figure 20) (Smedley and Allen, 2004). However, recent detailed gravity modelling (Taylor, 2007) suggests that the subsurface geometry of these batholiths may be more restricted, with each having a more tabular form, with their bases in the range of 3 to 4 km depth (Figure 21). This model would suggest that the extent of the granite in the depth range of interest will not be significantly greater than the area of outcrop of each of the plutons.

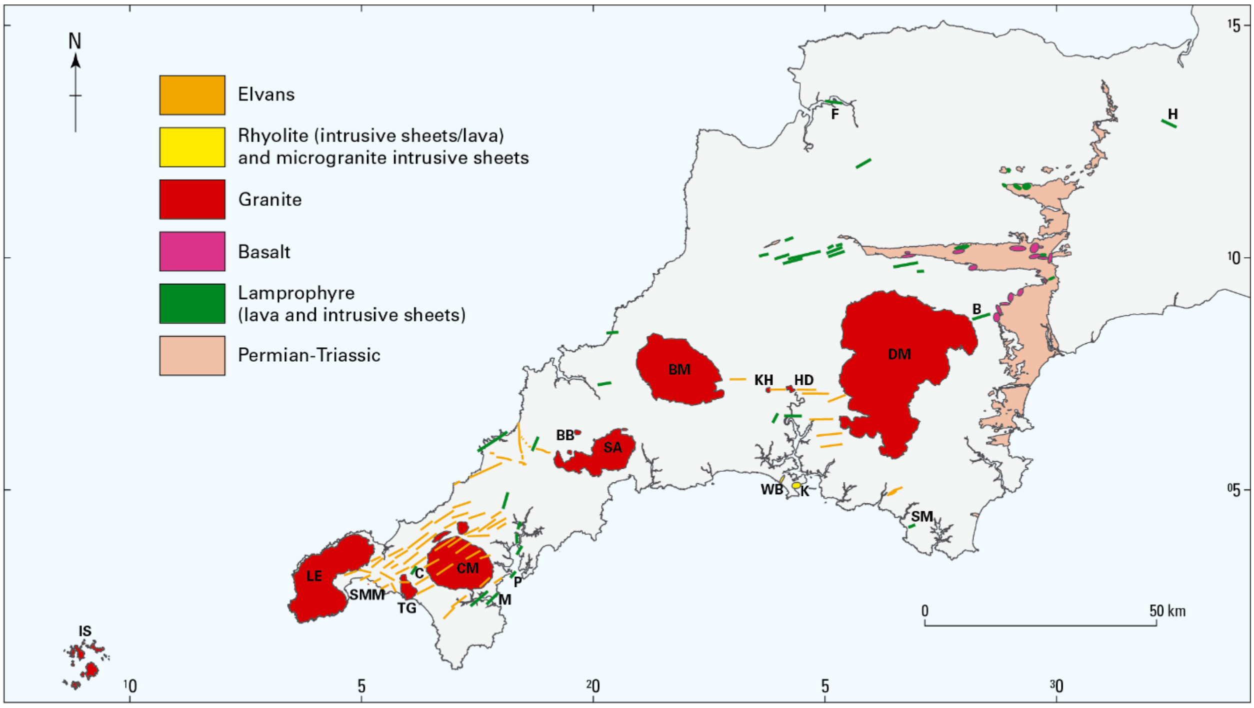

Figure 19 Post-Variscan igneous rocks in South-west England with the exception of the Palaeogene Lundy Island granite. Granites: BB, Belowda Beacon; BM, Bodmin Moor; CH, Cligga Head; CM, Carnmenellis; DM, Dartmoor; HD, Hingston Down; IS, Isles of Scilly; KH, Hit Hill; LE, Land's End; SA, Saint Austell, SAB, St Agnes Beacon; SMM, St Michael's Mount; TG, Tregonning-Godolphin. Rhyolite: K, Kingsand; WB, Withnoe-Bridgemoor. Lamprophyres: B. Bridford; C, Chyweeda; F, Fremington; H, Hestercombe; SM, South Milton; M, Mawnan: P, Pendennis. British Geological Survey © UKRI 2018

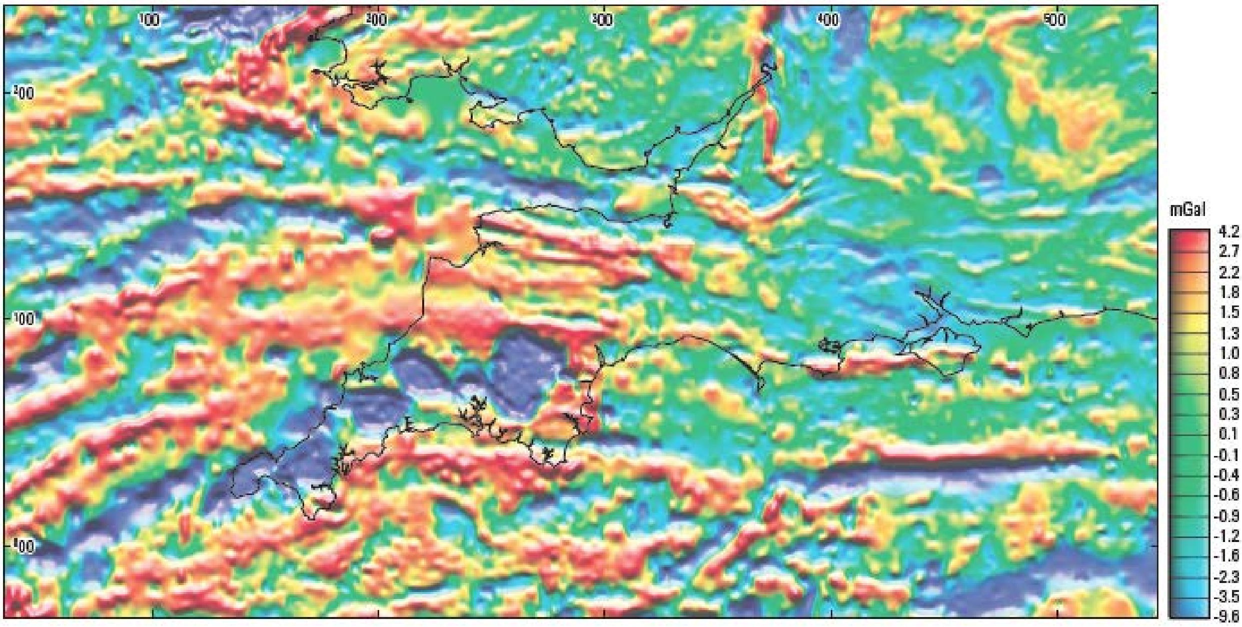

Figure 20. Bouguer gravity map of South-west England showing the regional negative gravity anomaly associated with the major granitic plutons. British Geological Survey © UKRI 2018

Limited borehole evidence does show evidence that the major plutons extend spatially beyond their outcrops and possibly link up in the subsurface in places. For example, the Devon Great Consols D3 and Redmoor RM82-29 boreholes (Figure 3), between Bodmin Moor and Dartmoor, encounter felsic (granitic) igneous rock at 556 m and 520 m bgl respectively, beneath Late Devonian sedimentary rocks. Along with limited outcrops of granite west of Tavistock at Gunnislake, these boreholes suggest that the Bodmin and Dartmoor plutons link up in the subsurface. Borehole evidence is lacking, however, to prove similar links between the other major plutons.

Most of the plutons are composed of biotite granite, with less common tourmaline granite and topaz granite (Smedley and Allen, 2004). The granites underwent widespread mineralisation with hydrothermal activity after emplacement and there are many historic mines in the granites and surrounding areas exploiting this mineralisation (Smedley and Allen, 2004). Boreholes and mines in excess of 2500 m in the Carnmenellis granite indicate that the composition does not change significantly with depth (British Geological Survey, 1990; Burgess et al., 1982).

The intrusions are also responsible for significant thermal metamorphism in the surrounding sedimentary country rocks. For example, the Tavy Formation around the Bodmin and Dartmoor (and intervening Gunnislake) outcrops are hornfelsed for a distance of up to 1.5 to 2 km from the margin of the granites. The term hornfels refers to the effects of thermal metamorphism on sedimentary rocks, which tends to render them harder and more massive (i.e. remove any original fissility or layering). This is the case for many of the formations extending around the width of these plutons in the south-west, for example, the Mylor Slates Formation are hornfelsed for about 1 to 3 km away from the outcropping margins of the Land’s End and Carnmenellis granites. Taylor (2007) notes that the width of the metamorphic aureoles around the Dartmoor, Bodmin and St. Austell plutons is strongly asymmetric, being wider (up to 3 km) on their northern sides as opposed to their south (around 1 km), suggesting a shallower dip to the granite contacts on their northern sides. This is supported by observation in the Radnor 16 St Agnes borehole (Figure 3) of granite at 362 m bgl (beneath Mid Devonian sedimentary rocks), several kilometres to the north of the northern margin of the Carnmenellis pluton and its satellite outlying plutons, suggesting a relatively shallow-dipping northern margin. This implies that granite will be encountered within the lower part of the depth range of interest for at least 4 km north of the margin of the pluton in this area, and also by implication to a similar distance on the northern margin of the other plutons in the region.

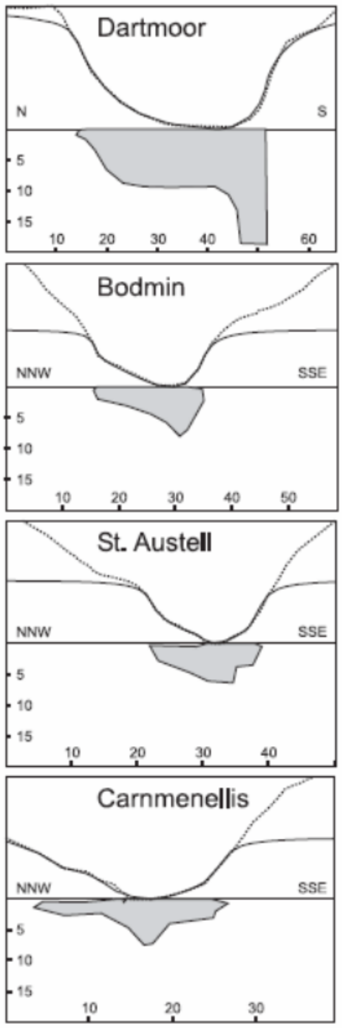

Figure 21 Gravity models for the (a) Dartmoor, (b) Bodmin, (c) St. Austell and (d) Carnmenellis plutons. Depths are in kilometres and horizontal scale has tickmarks at 10 km intervals. Dotted lines are the observed Bouguer gravity data; continuous lines the modelled gravity data (from Taylor, 2007) © Geological Society of London.

Principal information sources

Information on lithology and distribution of the granites comes principally from surface outcrop mapping, including analysis of both inland and coastal exposures. These are described at length in various publications and form the basis for the NGS3D model and cross-sections. Some borehole evidence is also available that enables inference on the geometry of the granite intrusion margins. Geophysical evidence, principally gravity, is used to infer the geometry of the granites at depth.

4.2.2.3 UNDIVIDED TEIGN VALLEY AND TINTAGEL GROUPS — HSR

This PRTI is early Carboniferous in age, and occurs across a large part of the central and north-east of the region, beneath younger Carboniferous rocks (principally the Holsworthy Group, a non-PRTI). It comprises chert-dominated sediments, with subordinate siliceous mudstones and mudstones, passing down into a thick sequence of slaty or shaly mudstones, with subordinate siltstone and sandstone, and locally important volcanic sequences. The lower part of the group is therefore most compatible with the HSR (slaty mudstone) PRTI category, although the upper, chert-dominated sequences do contain significant mudstone units that could comprise PRTIs.

Structurally, the Teign Valley and Tintagel groups form part of a complex, east–west-orientated, synclinal feature (‘synclinorium’), cored by Carboniferous rocks and underlain by Devonian rocks, which extends across much of central Devon including the Barnstaple, Bodmin Moor and Dartmoor areas (Figures 4 and 5). The Carboniferous rocks in this area form the ‘Culm basin’ as described by Leveridge and Hartley (2006).

The groups crop out on the north and south flanks of the Culm basin (Figure 17, shown in dark blue colour - Mississippian).

The Teign Valley and Tintagel groups are approximately 1000 m thick (Waters et al., 2015) and, where not at outcrop, are often buried beneath a thick sequence of Holsworthy Group (Figure 22, blue = Teign Valley and Tintagel groups; green = Holdsworthy Group). The groups occur in the depth range of interest on structural (folded) highs across the central Culm basin (conjectured from surface mapping), and also where it dips up towards the surface outcrops in the south and north flanks of the basin.

The northern outcrop runs in a narrow belt inland from Barnstaple eastwards towards Wellington, and the groups then dip southwards beneath the Holsworthy Group and above Late Devonian rocks. It lies within the depth range of interest in a belt between 1 and 10 km wide south of this outcrop line, narrowest in the west where the dips are steepest (taking it rapidly below the depth range of interest), running approximately from between Bideford and Barnstaple in the west and between Wellington and Tiverton in the east. It extends towards the east beneath the Mesozoic cover but generally below the depth range of interest.

The southern outcrop forms a more discontinuous but wider (2–20 km wide) belt running inland (and offshore to the west) from Boscastle towards the west side of Dartmoor, continuing to the east of Dartmoor south of Exeter. Beneath the outcrops between Bodmin Moor and around Callington, the thickness of the groups present is sufficient to only just reach the uppermost depth range of interest before the underlying Late Devonian rocks are encountered (here overlying an uplifted ‘block’ above Late Devonian rocks). However, in the northern part of this outcropping belt and towards the north-east, into the main synclinal ‘Culm’ belt, the Teign Valley and Tintagel groups descend significantly into the depth range of interest, dipping beneath Holsworthy Group rocks in a belt extending in the subsurface for up to 5 km north of its outcrop as far as a line between Holsworthy in the west and Exeter in the east.

Principal information sources

Information on the thickness and lithology of the Teign Valley and Tintagel groups comes almost exclusively from surface outcrop mapping, principally from coastal exposures on the north and west coasts of Devon and Cornwall. Borehole evidence is very limited, with very few boreholes reaching more than tens or a few hundred metres in depth, as is the case across much of the Palaeozoic outcrop in the South-west England region. The Wilsey Down borehole (Figure 3), some 12 km east of Tintagel, is, however, one of very few deep boreholes, proving 709 m of the groups (beneath 52 m of Holsworthy Group sediments), providing useful lithological information.

Rock type descriptions

The Teign Valley and Tintagel groups consist mainly of mudstone, but chert and other lithologies are locally dominant at various stratigraphical level. They are represented by a variety of named formations, representing both vertical and lateral stratigraphical complexity but also local nomenclature created by multiple generations of BGS mapping. Figure 22 illustrated the lithological variations of the Teign Valley and Tintagel groups in the North Devon, Culm and South Devon basins.

North Devon

The Teign Valley and Tintagel groups in north Devon occur in two areas. In the area around Barnstaple (to the west and north of the east–west-trending Brushford Fault), they are represented by the Codden Hill Chert Formation and the underlying Doddiscombe Formation (Figure 22). To the east and south of the same fault, in the area to the west of Wellington, they are represented by the Dowhills Mudstone Formation, the Bampton Limestone Formation and the Doddiscombe Formation (in descending stratigraphical order).

The Codden Hill Chert Formation comprises 150–190 m of shaly mudstone (locally siliceous) and chert, with the proportions of each lithology varying locally (BGS Lexicon). The Doddiscombe Formation consists dominantly of mudstone (BGS Lexicon), and is about 80 m thick, as does the Dowhills Mudstone Formation (BGS Lexicon), which is around 30 m thick. The Bampton Limestone Formation comprises interbedded chert, limestone and shale, around 80 m thick (BGS Lexicon).

South Devon–north Cornwall

In this area, the Teign Valley and Tintagel groups have a more extensive but fragmented outcrop, which has resulted in a complex formational stratigraphy being defined and used to describe both lithological and structural variations. However, the overall sequence is generally similar to that of the north Devon Teign Valley and Tintagel groups outcrop, with chert-dominated lithologies passing downwards to more mudstone-dominated lithologies (including interspersed volcanics).

This area contains the major Bodmin Moor and Dartmoor granite plutons, which have significant thermal metamorphic aureoles, resulting in 'hornfelsing' of the surrounding sedimentary sequences in zones up to 1–2 km wide.

Thicknesses within the sequence are difficult to estimate accurately due to structural complexity (e.g. thrust/fold repetition and faulted stratigraphical boundaries), so any thicknesses given are only approximate.

Towards the western Boscastle and Tintagel end of their south Devon–north Cornwall outcrop, the Teign Valley and Tintagel groups' sequence is estimated to be around 160 m thick, although this is very approximate due to complex deformation (BGS Lexicon; Freshney et al., 1972). The rocks are preserved in a series of thrust fault-bounded structural slices, in places alternating with the overlying late Carboniferous and underlying Late Devonian sequences (Freshney et al., 1972).

These sequences extend in a fragmented narrow (around 1.5 km wide) outcrop around the north side of Bodmin Moor, widening to a broader (up to 15 km wide) belt in the area to the west of Dartmoor (around and to the south of Launceston to Tavistock). In broad terms, the early Carboniferous rocks in this area lie in synclinal fold cores (affected by much faulting/thrusting) above Late Devonian rocks, and are estimated to extend to about 400 m depth i.e. into the upper part of the depth range of interest. The overall sequence is shown in Figure 22.

The Codden Hill Chert Formation (Teign Valley Group) consists of cherts, cherty siltstones and black slates (Freshney et al., 1972). The Wilsey Down borehole (Figure 3), some 12 km east of Tintagel, proves 709 m of the Teign Valley and Tintagel groups (beneath 52 m of Holsworthy Group mudstone, siltstones and sandstones), which are all assigned to the Fire Beacon Chert Formation in the log interpretation. It comprises principally dark grey slates with subordinate limestones and is only described as cherty in between 316 and 415 m depth. It is surmised here, however, that the lower part of the borehole below 415 m may represent at least in part the Teign Valley and Tintagel groups underlying the Fire Beacon Chert Formation.

The Visean Trambley Cove Formation of the Teign Valley Group is represented by siliceous slates with frequent siltstones, and reaches 15 m in thickness (BGS Lexicon). The laterally equivalent Famennian–Visean Buckator Formation (Teign Valley Group) (BGS Lexicon) comprises slates with a few limestones. Its thickness is approximately 30 m but not known accurately due to isoclinal folding and low-angle faulting (McKeown et al., 1973; Freshney et al., 1972; BGS Lexicon).

The Tintagel Volcanic Formation (Teign Valley Group) consists of 90 m of tuffs, agglomerates and lavas (BGS Lexicon; Freshney et al., 1972).

The Barras Nose Formation (Teign Valley Group) comprises slates with thin beds of siltstone, tuff and limestone, and is 21 m thick (BGS Lexicon).

Towards the central part of its south Devon–north Cornwall outcrop, in the Launceston–Tavistock area and to the north of Dartmoor (Okehampton area), the Teign Valley and Tintagel groups' sequence is represented (in broadly descending order, owing to uncertainties in lateral correlation and structural complexity) as follows.

The Teign Chert and Codden Hill Chert formations (laterally equivalent) correlate with the Fire Beacon Chert Formation to the west, and with the Codden Hill Chert Formation in the upper part of the Teign Valley and Tintagel groups in the northern outcrop, with thickness estimated at 190 m (BGS Lexicon). The lithology is described as siliceous mudstones, shaly mudstones and cherts (BGS Lexicon). The Bovey Tracey G1 borehole (Figure 3) proved over 125 m of dark grey mudstones with subordinate (sub 1 m scale) chert horizons.

The Meldon Shale and Quartzite Formation (equivalent to the Buckator Formation further west (McKeown et al., 1973)) comprises black, shaly mudstones with (generally less than 50 per cent volume) thin beds of quartzite (up to 15 cm thick (BGS Lexicon)), and outcrops mainly around Okehampton. Thickness is given as 126–161 m (BGS Lexicon).

The Brendon Formation forms a significant part of the outcropping Teign Valley and Tintagel groups in the areas to the south of Launceston and Tavistock. It comprises dark grey, locally siliceous mudstone with thin beds of siltstone with some tuff and basaltic lava units. Thicknesses are difficult to estimate due to all observed contacts being tectonic (BGS Lexicon), but is estimated as 450 m.

The St Mellion Formation forms another significant part of the outcropping Teign Valley and Tintagel groups in the Launceston–Tavistock area but is also found to the east of Dartmoor around Ashburton. It comprises interbedded dark grey sandstone and mudstone, and as with the Brendon Formation, its thickness is difficult to estimate, but is in the order of 500 m (BGS Lexicon).

Beneath the outcrops between Bodmin Moor and around Callington, the preserved thickness of the group present is sufficient to only just reach the uppermost depth range of interest in synclinal cores (e.g. around Callington and just north of Tavistock) before the underlying Late Devonian rocks are encountered. However, a significant, northerly inclined Variscan fault structure, running broadly east–west close to Launceston, means the Teign Valley and Tintagel groups drop to its north into the depth range of interest, remaining within it in a belt extending about 7 km north of this line before the northward dip takes it below the depth range of interest (beneath the Holsworthy Group) towards the centre of the Culm basin.

Towards the eastern part of it south Devon–north Cornwall outcrop, to the north-east and east of Dartmoor and across to east Devon, the Teign Valley and Tintagel groups are represented by narrow (several kilometres wide at most) outcrops, comprising the following principal units.

The Ashton Mudstone Member forms isolated, fault-bounded outcrops (approximately 10 km by 2 km in extent) in the area west of Exeter and also in a linear outcrop (10 km long, 250 m wide) at the top of the Teign Valley and Tintagel rocks to the east side of Dartmoor near Chudleigh. It is transitional with the overlying Holsworthy Group and comprises 210–430 m of greyish-blue, rusty mudstones with scattered thin (up to 7 cm) siltstone and sandstone beds.

The Teign Chert and Codden Hill Chert formations are described at outcrop some 8 km south-west of Exeter as comprising up to 240 m of bedded cherts with interbedded tuffs (Edwards and Scrivener, 1999). These units comprise between 150 and 230 m of cherts and siliceous mudstones, with mudstone generally subordinate (BGS Lexicon).

The Combe Mudstone Formation comprises fissile, black shales with silty laminations, and is some 45 m thick in the Chudleigh area (BGS Lexicon).

The Trusham Mudstone Formation comprises olive green and pale grey shale, some 65 m thick, in the Chudleigh area.

A combination of eastward dip away from the margin of the Dartmoor granite, plus omission by Variscan thrust structures, means that these units occur only in the upper third of the depth range of interest in a belt up about 3–5 km wide around the eastern margin of Dartmoor.

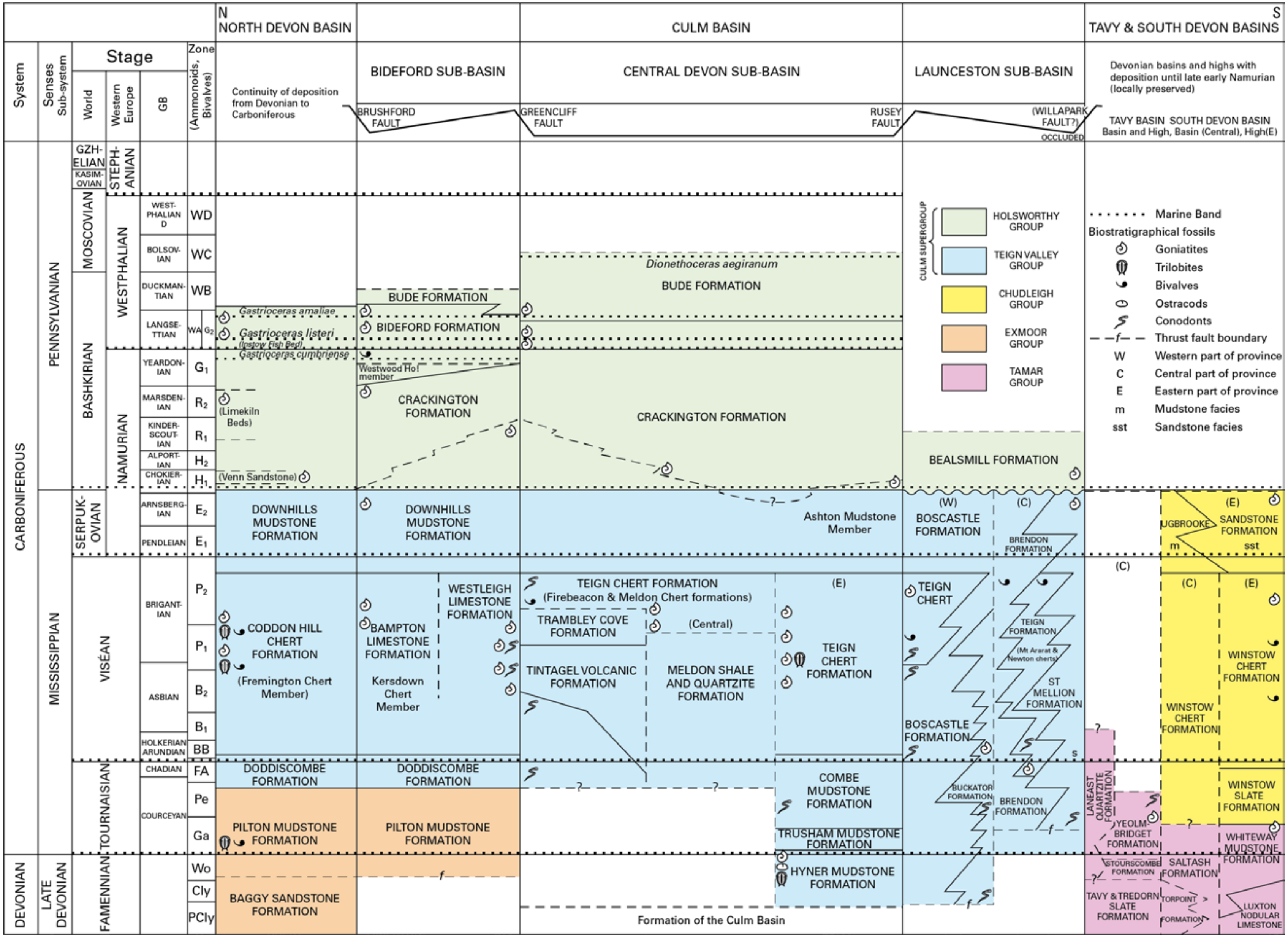

Figure 22 Stratigraphic and correlation chart of the Carboniferous and Devonian rocks of the North Devon, Culm, Tavy and South Devon basins. British Geological Survey © UKRI 2018

4.2.2.4 UNDIVIDED LATE DEVONIAN ROCKS — HSR

This unit represents a variety of sedimentary rocks across the region. They principally occur in two main areas: close to the very north of Devon and north-west Somerset, and in Cornwall with a small extension into south-west Devon. These sequences accumulated in a range of separate basins during continental margin rifting, each with their own depositional and subsequent tectonic history (Leveridge and Hartley, 2006), meaning wider lateral correlations across the South-west England region are not useful. However, more localised successions are identified (Figure 22), which can be used to draw conclusions on the potential distribution of HSR (slaty mudstone) PRTIs.

Lithological variations within Late Devonian sediments in Cornwall and south Devon are related to deposition in a series of variably interconnected basins, developing sequentially from south-west to north-east (Gramscatho, Looe, South Devon and Tavy) (Figure 22, Tavy and South Devon basins). Sequences were deposited in deeper water 'basinal' settings with intervening highs, resulting in lateral variability from mudstone-dominated to sandstone and limestone-dominated sequences (principal aquifers, described in Section 6) respectively. Variable rifting activity driving the development of these basins also produced vertical variations in the predominance of mudstone. Such variations form the basis of a complex formational stratigraphy. Late Devonian rocks also developed in the major north Devon basin (Figure 22, North Devon basin) but the relationship to the basins above is not well constrained due to their geographical separation by the intervening Culm basin.

Sequences developed in these basins reach significant thicknesses, with individual formations varying from hundreds to thousands of metres thick. Mudstone-dominated packages of 500 m thick or more are seen at various levels, often affected by significant cleavage development related to subsequent Variscan deformation. Thermal metamorphism around the margins (in bands up to 1–3 km wide) of the major Cornubian batholith intrusions is also seen, resulting in hornfelsing.

Late Devonian rocks occur widely within the depth range of interest in the southern basinal areas of Cornwall, south Devon and the north Devon area, but lie generally below the depth range of interest beneath the central Devon (Culm basin) region, where they are overlain by thick Carboniferous sequences.

Dating of these Devonian sequences is based primarily on ammonoid, conodont and ostracod palaeontological evidence (e.g. Freshney et al., 1979).

Principal information sources

Information on the thickness and lithology of the Late Devonian successions comes almost exclusively from surface outcrop mapping, principally from coastal exposures around Devon and Cornwall. These are described at length in various BGS memoirs and sheet explanations and form the basis for the NGS3D model and cross-sections. Borehole evidence is very limited, with very few boreholes reaching more than a few hundred metres in depth, and none constraining the boundaries of formations within the Late Devonian.

Rock type descriptions

There are three principal outcrop areas for Late Devonian rocks in the region: north Devon; north Cornwall–south Devon, and south Cornwall.

North Devon

Rocks of Late (formerly 'Upper') Devonian age in north Devon include the following formations (Edmonds et al., 1985; Leveridge and Hartley, 2006; BGS Lexicon), as shown on Figures 23 and 24.

The Baggy Sandstones Formation consists dominantly of sandstones and is approximately 450 m thick. Note, this is overlain by the 500 m-thick, mudstone-dominated Pilton Mudstone Formation (= Pilton Shale), which extends from the Late Devonian into the lower part of the early Carboniferous but is included within the Late Devonian category in the present analysis.

The Upcott Slates Formation consists of mudstone and siltstone-dominated rocks, and is 250 m thick.

The Pickwell Down Sandstones Formation forms the middle part of the Late Devonian and is a 1200 m-thick sandstone-dominated sequence.

The Morte Slates Formation is 1500 m thick and grades down from (pro-deltaic) fine-grained sandstones in the upper third to shallow marine mudstones and siltstones in the lower two thirds.

The Upcott Slates and Morte Slates formations, therefore, are the most compatible with the HSR (slaty mudstone) PRTI category.

These formations form strands within the broad 9 km-wide outcrop of the Late Devonian across north Devon, between Barnstaple and Ilfracombe on the coast to the south of the Quantock Hills north of Wellington. The thickness of the formations (totalling nearly 4 km thick) means that the lower part of the succession (the Morte Slates Formation in particular) are within the depth range of interest beneath much of this area of outcrop. A southward dip towards the Culm basin means they extend within the depth range of interest at depth for some 5 to 7 km to the south of the outcrop, as far as a line approximately from Bideford on the coast to Tiverton in the east. An anticlinal structure (the Quantock Anticline), trending west-north-west north of Taunton, brings these rocks up into the depth range of interest in a broad area between Bridgwater and several kilometres south of Taunton (partly beneath Mesozoic cover).

The thickness of the overlying Carboniferous rocks means that Late Devonian rocks are below the depth range of interest beneath much of the central Culm basin, apart from in a few, conjectured structural (folded) highs where the upper part (Pilton Mudstone Formation) extends up into the depth range of interest. A general eastwards plunge in the Culm Basin Syncline, however, means Teign Valley and Tintagel rocks rise more consistently to within the depth range of interest in the western extent of the Culm basin area, in the area to the west of Petrockstowe as far as at least the west coast.

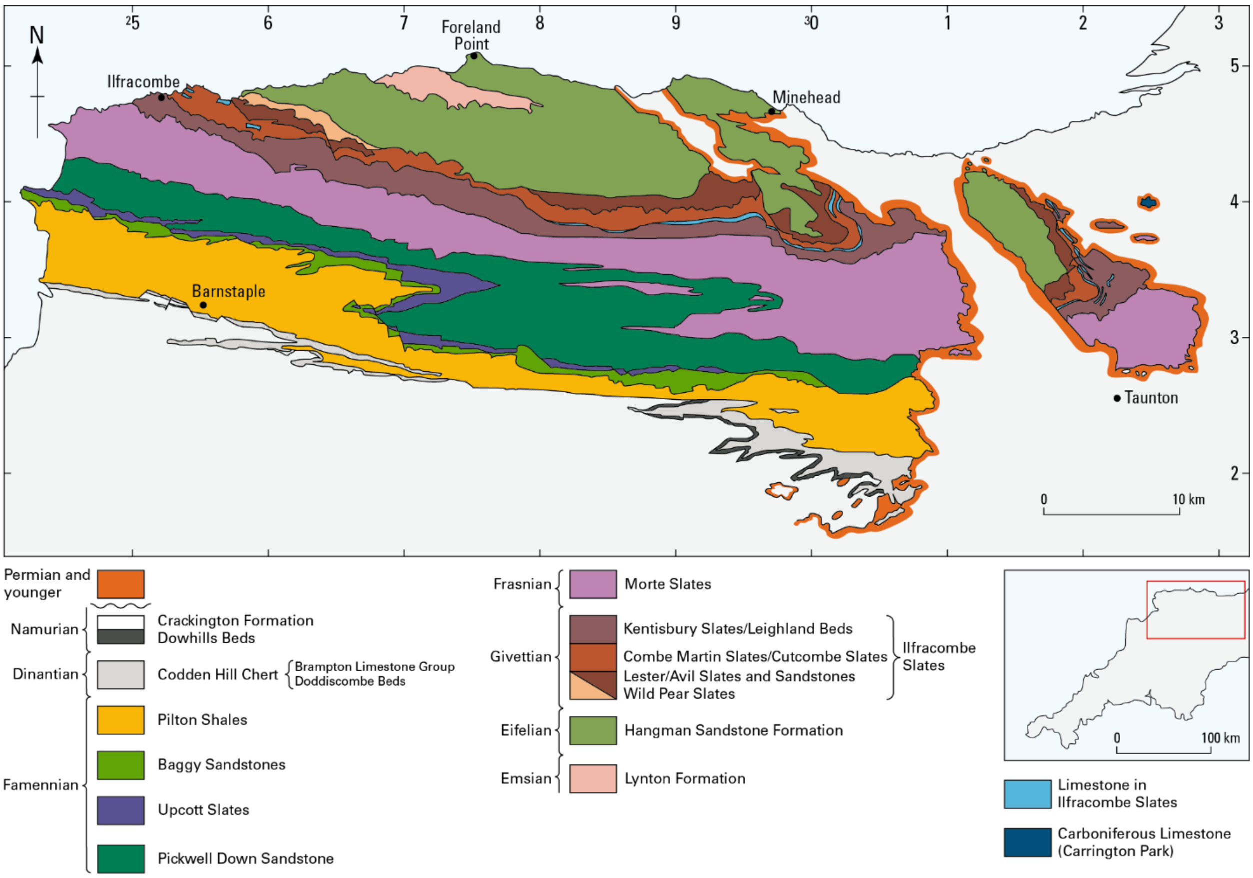

Figure 23 Sketch geological map of the Devonian and Early Carboniferous rocks of the North Devon basin and correlations within the adjacent Bideford sub-basin. Note some of the stratigraphical nomenclature shown have been superseded (see BGS Lexicon). British Geological Survey © UKRI 2018

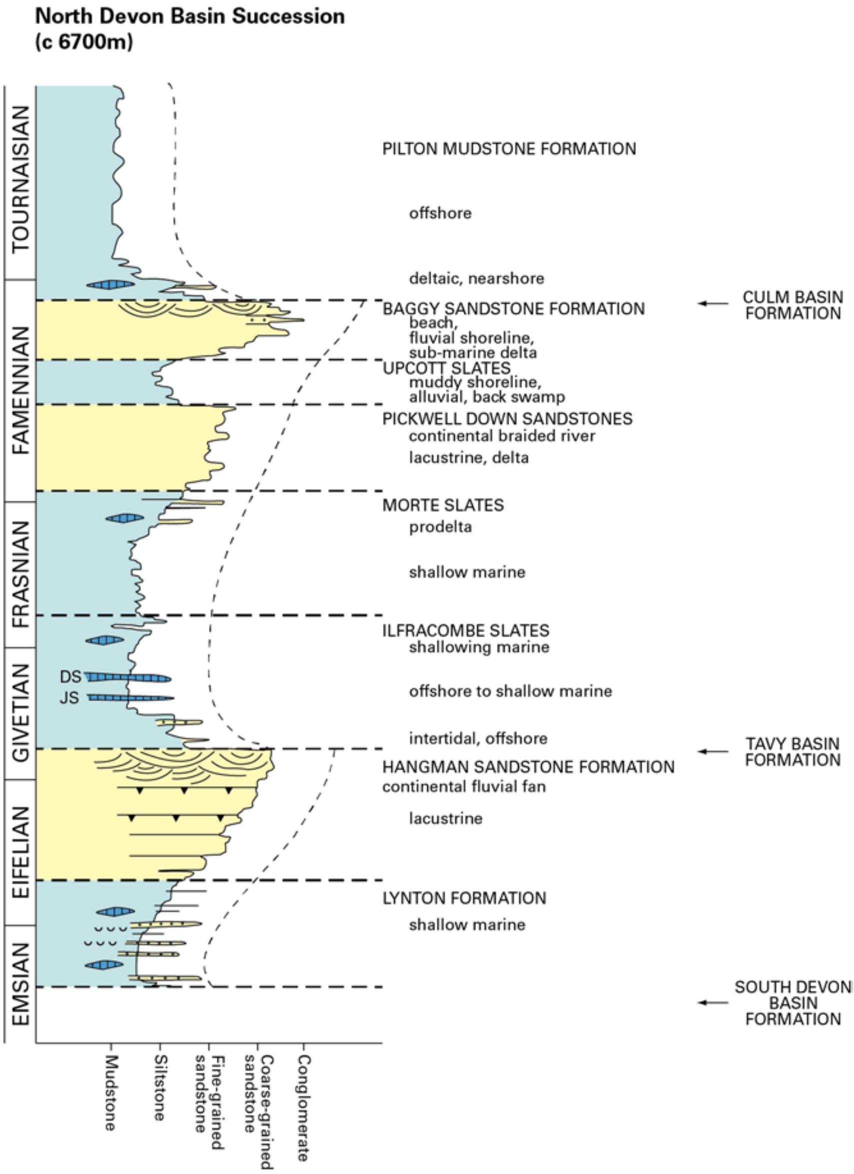

Figure 24 Graphical log showing the major sedimentary cycles constituting the North Devon basin succession. Note some of the stratigraphical names have now been superseded. Modified from Leveridge and Hartley, 2006. © Geological Society of London.

North Cornwall–south Devon

Towards the western end of this outcrop area, around Trevose and Tintagel on the west Cornish coast, the Late Devonian is represented principally by the following formations (in descending order), all dominated by mudstone (shaly or slaty) and hence PRTIs.

The Yeolmbridge Formation (part of Tamar Group, the top extending into the early Tournaisian) forms a narrow, 400 m-wide outcrop extending 12 km inland south-eastwards from the coast just north of Tintagel, with further isolated small (sub 1 km wide) outcrops extending further inland to some 10 km east of Launceston. The main part of this outcrop lies in a structurally controlled, northerly inclined thrust slice beneath overthrust Carboniferous rocks. It comprises up to 100 m of dark-coloured mudstones with variable amounts of siltstone laminae and rare thin sandstones and limestones, with locally present volcanic rocks (BGS Lexicon). It is unlikely to extend significantly into the depth range of interest before being cut out by the thrusting.

The Tredorn Slate Formation (part of Tamar Group and the lateral equivalent of the Tavy Formation further to the east) crops out along a 10 km stretch of coastline to the north and south of Tintagel, extending inland by up to 20 km to the east-south-east; the outcrop is separated into two components by the intervening (up to

90 m thick (BGS Lexicon)) Tintagel Volcanic Formation. The upper and lower boundaries of the Tredorn Slate Formation are structurally controlled (thrusted), but the unit is estimated to be between 500 to 800 m thick (BGS Lexicon). It comprises greenish-grey quartz-chlorite-mica slate, with thin interbeds (15 cm) of limestone, sandstone and siltstone, and rare tuff beds. A northward dip brings the formation within the depth range of interest in a 6 km wide zone to the north-east of a line extending from Tintagel through Camelford. To the south, the formation is intruded by the Bodmin Moor granite, so would be expected to be hornfelsed around the granite margins in a zone up to about 1 km wide; a relatively shallow northward dip of the granite contact means the granite may be intersected beneath the Tredorn Slate Formation at depths shallower than the depth range of interest for a zone extending some 2 km north of the outcropping granite margin (Waters et al., 2015; DiGMAPGB-50 (BGS 1:50 000 digital geological data)).

The Polzeath Slate Formation occurs in a limited 2 by 12 km outcrop, intersecting the coast just north of Padstow. It comprises between 240 and 320 m of cleaved purple mudstone with thin siltstone and sandstone laminae and more continuous horizons (BGS Lexicon). It lies in a broad synclinal fold core above the Harbour Cove Slate Formation, and hence is likely to occur within the only in a limited area beneath the centre of its outcrop.

The Harbour Cove Slate Formation also crops out near Padstow, adjacent to the overlying Polzeath Slate Formation. It comprises between 260 and 600 m of homogeneous grey and grey-green slaty mudstone with local tuff units up to 100 m thick. The broad synclinal form means it is likely to extend into the upper part of the depth range of interest beneath much of the outcrop of the overlying Polzeath Slate Formation, extending some 12 km inland from Padstow Bay.

Towards the central part of the north Cornwall to south Devon area, between Bodmin Moor and to the west of Dartmoor, the Late Devonian is represented principally by the following formations (in descending order), all dominated by mudstone (shaly or slaty) and hence PRTIs.

The Liddaton Formation comprises grey and greenish slate with siltstone and sandstone laminae (BGS Lexicon). It has a relatively limited, linear and fragmented outcrop (up to 1.5 km wide and 25 km long) extending from Launceston towards Dartmoor. The contacts are thrusted so the thickness is not known (BGS Lexicon) but it is likely only to be in the order of 100 to 200 m (estimate made here). It is only likely to extend into the upper part of the depth range of interest in a limited area to the north and south of its crop.

The Tavy Formation (Tamar Group) consists of well-cleaved, pale green and grey-green, chloritic silty mudstone within minor thin (up to 0.1 m thick) sandstone beds (Leveridge et al., 2002; BGS Lexicon). The Tavy Formation has a principal outcrop (some 15 km by 20 km in extent) in the area between around Callington and to the south of Tavistock, extending around the southern end of Dartmoor up to Ashburton on its eastern side (Waters et al., 2015). Its boundaries are generally transitional or thrust faulted so the thickness of the formation is uncertain (BGS Lexicon), though is likely to be substantial (in the order of 500 m to several kilometres thick, from the extent of the outcrop). The formation is hornfelsed around the Dartmoor granite in an aureole up to 2 km wide. The unit is present within the depth range of interest in three main zones:

- A general synclinal form beneath Carboniferous rocks around Callington means the Tavy Formation is likely to occur within the depth range of interest in a broad area extending from not far to the north of the southern margin of its outcrop (some 4 km south of Callington), beneath Callington itself, and also in the area to the north of the Carnmenellis granite intrusion where the formation dips to the north again beneath Carboniferous cover.
- The formation remains in the depth range of interest in a broad belt extending further to the east from Callington towards Ivybridge to the south of Dartmoor, where it is bounded by a major southerly inclined Variscan thrust and does not extend in the depth range of interest to the south of Ivybridge.
- To the east of Dartmoor, a general south-east dip, and a similar occurrence of southerly inclined thrust structures, means the formation occurs in the depth range of interest in a narrow (around 1 km) belt extending 10 km south-eastwards from Ashburton.

The Torpoint Formation (Tamar Group) principally comprises purple and green slaty mudstone with subordinate siltstone laminae, and outcrops in a series of 1 to 1.5 km-wide, east–west linear belts that interdigitate with the Saltash Formation; the outcrop pattern is further complicated due to a complex network of thrust faults and later extensional faults (Leveridge et al., 2002). The upper stratigraphical boundary of the formation is nowhere observed, so thickness can only be estimated from the scale of the individual outcrop ‘slices’, which suggest a minimum of 100 to 200 m (estimate made here). The principal outcrop area extends westwards from Plymouth towards Liskeard, and, along with the Saltash Formation, the general southwards dip of the formation takes it into the upper part of the depth range of interest beneath much of its outcrop area, bounded to the south by Variscan thrusting.

The Saltash Formation (Tamar Group) comprises predominantly grey, slaty mudstone and silty mudstone with significant subordinate lithologies, notably volcanic rocks, limestone and sandstone. It ranges in age from Early Devonian to early Carboniferous (Leveridge et al., 2002), but is included here as it interdigitates with the Torpoint Formation. Its principal outcrop area is similar to but more extensive than the Torpoint Formation, extending westwards from Plymouth past Liskeard. Its lateral equivalents to the west are the Trevose Slate and Rosenum formations, which are described under the Mid Devonian section. Its thickness is estimated from exposures on the north Cornwall coast at 3900 m. In the Plymouth area, the formation extends into the upper part of the depth range of interest beneath much of its outcrop area and, as with the Saltash Formation, is bounded to the south by Variscan thrusting.

Towards the eastern part of the north Cornwall to south Devon area, east of Dartmoor, the Late Devonian is represented principally by ‘basinal’ facies slates and shales (representing HSR PRTIs), which pass laterally into limestone-dominated facies associated with depositional ‘highs’ (Figure 25). This slate/shale-dominated sequence includes the following, largely laterally equivalent formations (in places lumped together simply as ‘Late Devonian slates’ on BGS DiGMapGB-50 (BGS 1:50 000 digital geological data)).

The Tavy Formation is present, as described previously.

The Hyner Mudstone Formation (‘Hyner Shale’ on Figure 25) has a limited, 7 km-long outcrop around the north-east margin of Dartmoor just to north of Chulmleigh, extending up to 1.5 km from the margin of the Dartmoor granite. The inner 1 km has been subjected to thermal metamorphism but outside of this aureole it comprises a hard, dark blue or bluish-green shaly mudstone, becoming calcareous towards the top and with subordinate siltstone beds (Selwood et al., 1984). The formation is estimated at 250 m thick (BGS Lexicon). An eastward dip away from the granite margin means it would be expected to dip through the depth range of interest in a narrow (about 2 km wide) zone to the east of the outcrop before it descends below the depth range of interest under Carboniferous strata.

The Gurrington Slate Formation (including local lateral equivalents, the Kate Brook Succession and the Rora Mudstone Formation; Figure 25) comprises greyish-green, purple and green slates with silty laminae, and rare siliceous nodules and horizons of siltstone (Selwood et al., 1984). The principal outcrop extends south-west from Newton Abbot for at least 15 km along strike, and 3 km across strike. The formation dips moderately towards the east, such that its base reaches the upper third of the depth range of interest beneath the eastern part of this outcrop area and up to 1 km to the east, where it is cut out (upfaulted and removed by erosion) by a major, southerly inclined Variscan thrust structure. The upper and lower boundaries of the formation are poorly constrained (Selwood et al., 1984), with no reliable mapping or borehole evidence, so thicknesses are very uncertain. However, the width of the outcrops suggests a thickness in the order of at least 500 m.

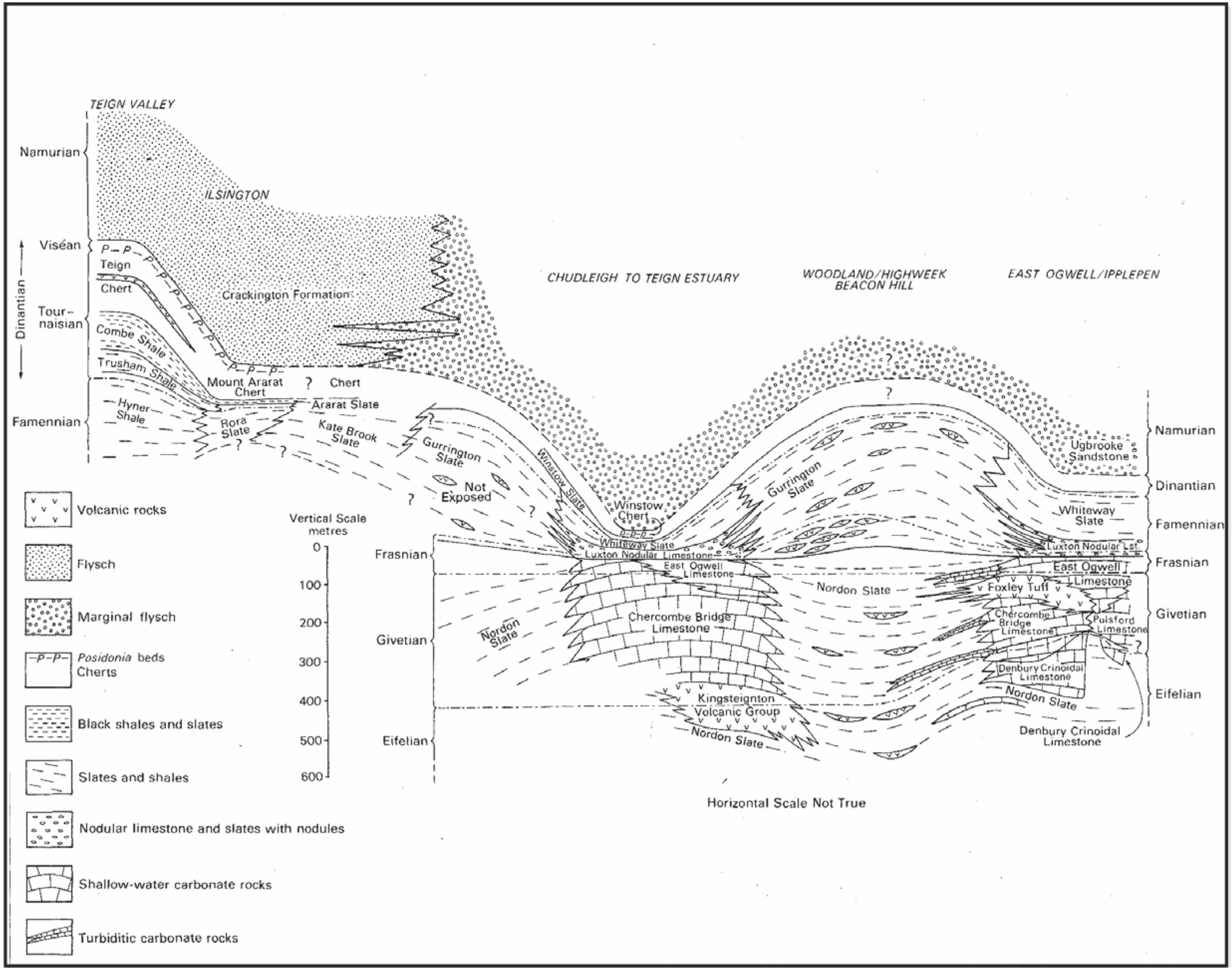

Figure 25 Facies relationships in Mid Devonian to late Carboniferous rocks of the Newton Abbot district (from Selwood et al., 1984). British Geological Survey © UKRI 2018

South Cornwall

In south Cornwall, the Late Devonian is represented principally by the Mylor Slate Formation, which is extensively exposed on the coast around the South-west England peninsula, where it comprises dominantly a variable grey-green, blue-grey or dark grey to black slate, commonly with pale grey or white silty laminae up to a few millimetres thick; rare impersistent sandstones also occur (Goode and Taylor, 1988). These slates are interbedded locally with basic lava, tuff and agglomerate, comprising 10 to 20 per cent of the Mylor Slate Formation (Isaac et al., 1998). The predominance of slate means that the whole formation is considered a HSR PRTI.

The whole Mylor Slate Formation sequence has been subjected to low-grade metamorphism and intense deformation relating to the Variscan Orogeny, with high-temperature thermal metamorphism (hornfelsing) in 1–3 km-wide, thermal metamorphic aureoles around the Land's End and Carnmenellis granite plutons.

Thickness information on the formation is limited, although the Cornish Land Ventures 10 borehole (Figure 3), some 3 km to the west of the Carnmenellis granite outcrop, proved 749 m of metasediments (assigned in NGS3D to Late Devonian). The Mylor Slate Formation is expected to extend into the upper half of the depth range of interest beneath much of its outcrop, which extends across south-west Cornwall between Newlyn and Porthleven on the south coast, across to St Ives on the north coast and eastwards around the Carnmenellis granite pluton to Falmouth. A relatively low-angle dip to the granite contacts means, however, that the granite may be encountered at relatively shallow depths for some distance from its outcropping margins. For example, the CM1 Camborne borehole (Figure 3), 1 km to the north-west outcrop margin of the Carnmenellis granite, proved granite at 200 m bgl beneath metasediments. The upper surface of the Cornubian batholith itself is inferred in NGS3D to extend at relatively shallow depths (between 700 and 1500 m) across much of the area between the Land's End and Carnmenellis granite plutons, such that it potentially occupies the lower part of the depth range of interest. However, recent studies suggest that the extent of the granites at depth may be more restricted.

4.2.2.5 UNDIVIDED MID DEVONIAN ROCKS — HSR

The distribution and origin of undivided Mid Devonian rocks in the South-west England region is similar to that for the Late Devonian, with three principal outcrop areas reflecting differing basin depositional histories: north Devon; north Cornwall–south Devon, and south Cornwall (Leveridge and Hartley, 2006). A series of localised successions are identified, which can be used to draw conclusions on the potential distribution of HSR (slaty mudstone) PRTIs.

Mid Devonian sequences developed in these areas reach significant thicknesses, with individual formations varying from several hundred to thousands of metres thick. Mudstone-dominated packages of 500 m thick or more are seen at various levels, often affected by significant cleavage development related to subsequent Variscan deformation.

Mid Devonian rocks occur widely within the depth range of interest in the southern basinal areas of Cornwall, south Devon, and also in the north Devon area but lie below the depth range of interest beneath the central Devon (Culm basin) region where they are overlain by thick Carboniferous and Late Devonian sequences.

Principal information sources

Information on the thickness and lithology of the Mid Devonian successions comes almost exclusively from surface outcrop mapping, principally from coastal exposures around Devon and Cornwall. These are described at length in various BGS memoirs and sheet explanations and form the basis for the NGS3D model and cross-sections. Borehole evidence is very limited, with very few boreholes reaching more than a few hundred metres in depth, and none constraining the boundaries of formations within the Mid Devonian.

Rock type descriptions

There are three principal outcrop areas for undivided Mid Devonian rocks in the region: north Devon; north Cornwall–south Devon, and south Cornwall.

North Devon

In north Devon, the principal HSR PRTI in the Mid Devonian is represented by the 545 m-thick Ilfracombe Slates Formation, comprising predominantly slates with subordinate siltstones, sandstones and limestones (Edmonds and Williams, 1985). Leveridge and Hartley (2006) shows them to be dominantly mudstone and siltstone in the upper two thirds (shallow marine deposits), grading down into siltstone to fine-grained sandstone sediments (intertidal/shallow marine deposits) in the lower third. The Ilfracombe Slates Formation overlies the Mid Devonian Hangman Sandstone Formation, which is sandstone-dominated and hence not a PRTI.

The Ilfracombe Slates Formation is exposed along the coast for 8 km to the east of Ilfracombe, with an outcrop of similar width extending inland eastwards from this almost as far as the Quantock Hills. It dips southwards from this outcrop under Late Devonian rocks and occurs at or below (depending on folding) the depth range of interest in a belt as far south as Bridgwater in the west and Wellington towards the east. Owing to a major anticlinal structure running west-north-west through the Quantock Hills area, the formation is horizontal to northerly dipping north of Taunton, and occurs in the depth range of interest as far north as Bridgwater. It is below the depth range of interest in the central Culm area beneath thick Late Devonian and Carboniferous rocks.

North Cornwall–south Devon

To the south and north of Padstow on the west Cornish coast, the Mid Devonian is represented principally by the undivided Trevose Slate and Rosenum formations. These comprise some 3900 m of grey, silty, laminated slate (hence an HSR PRTI) with regular thin (3 to 10 cm) siltstone beds, and sporadic sandstone and limestone beds particularly in the upper part of the formation (BGS Lexicon).

The formations are exposed on the west Cornwall coast in two main sections, the southern one 10 km long and the northern one 5 km long, to the south and north of Padstow respectively, separated by Late Devonian rocks occurring in the centre of an open synclinal structure (see Late Devonian section: Polzeath Slate Formation and Harbour Cove Slate Formation). The outcrop extends inland from this in a broad 10 km-wide swathe extending up to and around the south side of Bodmin Moor. The significant thickness of the formations, and a general open synclinal structure, means that they extend into the depth range of interest beneath much of this outcrop, intersecting the full width of the depth range of interest in a broad swathe northwards from Padstow and beneath the Late Devonian outcrop, as far north as a line east–west through Camelford. South of Padstow and Bodmin Moor the geological structure brings Early Devonian rocks nearer to the surface, meaning that the Trevose Slate and Rosenum formations only reach the upper part of the depth range of interest in the area between the towns of Wadebridge and Bodmin (and to their west and east).

Mid Devonian rocks also crop out in a 5 km-wide swathe running from the east of Plymouth nearly as far as Paignton on the south-east Devon coast, where they dip beneath Permian rocks. In this outcrop area, they are represented principally by the Nordon Formation (Torbay Group, also termed ‘Middle Devonian Slates’ in older terminology applied to the areas south of Ivybridge) and are likely to be of comparable thickness to the laterally equivalent Trevose Slate and Rosenum Slate formations (i.e. in the order of 3900 m). This formation comprises predominantly ‘basinal’ mudstones with thin siltstone laminae and thin beds of limestone that pass laterally into limestone-dominated sequences over the Torquay and Brixham ‘highs’ (Leveridge et al., 2004). The formation (and outcrop) is divided by the Ashprington Volcanic Formation, which comprises predominantly basaltic lava with subordinate volcaniclastic rocks.

Thicknesses for Mid Devonian sequences (the Nordon and Ashprington Volcanic formations together) are very poorly constrained by mapping or borehole evidence, partly due to the complex basinal high lateral variations and also structural complexity, however, the total Mid Devonian succession in south Devon is approximately 400–500 m (Waters et al., 2015). A series of north-directed thrust slices step the sequence downwards to the north beneath the Late Devonian sequences. As a result, the unit occurs in the upper part of the depth range of interest beneath its outcrop area, descending to the middle to lower part of the depth range of interest in a broad swathe north of a line from Totnes to Newton Abbot.

South Cornwall

Undivided Mid Devonian rocks in this area are represented by the following formations (in descending order).

The Porthtowan Formation (Eifelian to Frasnian) is predominantly a grey and green slate and hence a HSR PRTI. In the central part of the formation, sandstone and siltstone are present as classic, thin, turbidite beds. The formation is estimated to reach 2.8 km in thickness (Leveridge et al., 1990) and is exposed along the coastline for over 20 km between St Ives and St Agnes on the north Cornwall coast. Its outcrop extends inland in a 10 km-wide swathe as far as Truro, where it is overthrust by the Portscatho Formation. It significant thickness means that it is likely to extend into the upper part of the depth range of interest beneath the extent of its outcrop, shallowing (due to folding and thrusting) towards the south and west.

The Portscatho Formation (Givetian to Frasnian) comprises predominantly sandstone turbidites (2 m beds) with subordinate interbedded slaty mudstone and thin siltstones, and hence is not considered a PRTI. The Portscatho Formation is estimated to reach 5.4 km thickness (Leveridge et al., 1990; Goode and Taylor, 1988). It crops out across the southern part of the peninsula, to the south-east of the Carnmenellis granite, from north of the Lizard area to Mevagissey.

The Grampound Formation consists predominantly of grey slaty mudstone (hence a PRTI), with thin interbeds and laminae of siltstone and sandstone turbidites, and thin beds of limestone (BGS Lexicon; Leveridge and Hartley, 2006). This formation has a narrow, 1–3 km-wide outcrop running from the north-west Cornwall coast just north of St Agnes to the south-east coast just south of St Austell. Thicknesses are poorly constrained in the published literature due to structural complexity and a lack of borehole evidence. In the western part of its extent, the formation dips gently from outcrop beneath the Porthtowan Formation rocks and would be expected to reach the upper part of the depth range of interest beneath much of the outcrop of that formation. In the eastern part of its extent, the formation is cut out along the southern edge of its outcrop by thrusting against the Portscatho Formation, so is not expected to extend into the depth range of interest past its southern outcrop margin.

4.2.2.6 UNDIVIDED EARLY DEVONIAN ROCKS — HSR

The distribution and origin of Early Devonian rocks in the region is similar to that for the Mid Devonian, occurring in three principal areas reflecting differing basin depositional histories: north Devon; north Cornwall–south Devon, and south Cornwall (Leveridge and Hartley, 2006). The Early Devonian rocks occur partly at outcrop in the first two of these areas but only in the subsurface in the last. A series of localised successions are identified, which are used to draw conclusions on the distribution of HSR (slaty mudstone) PRTIs.

The Early Devonian sequences developed in these areas reach significant thicknesses, with individual formations varying from several hundred to thousands of metres thick. The sequences are generally mudstone-dominated, with significant cleavage development related to subsequent Variscan deformation, and hence are HSR PRTIs (see Table 2).

Early Devonian rocks occur widely within the depth range of interest in the southern areas of Cornwall and south Devon, and also in the north Devon area, but lie below the depth range of interest beneath the central Devon (Culm basin) region where they are overlain by thick Carboniferous and Mid–Late Devonian sequences.

Early Devonian rocks are inferred to occur in the offshore area of the outer Bristol Channel and north of the Devon and Cornwall coasts. These rocks occur within the depth range of interest and at (seabed) outcrop in the Lundy Island area, but dip below the lower limit of the depth range of interest in the offshore area north of Ilfracombe. Information regarding these offshore sequences comes exclusively from subsurface BGS seismic interpretations, and extrapolation from the published BGS 1: 250 000-scale offshore bedrock mapping (BGS DigRock250).

Principal information sources

Information on the thickness and lithology of the Early Devonian successions comes almost exclusively from surface outcrop mapping, principally from coastal exposures around Devon and Cornwall. These are described at length in various BGS memoirs and sheet explanations and form the basis for the NGS3D model and cross-sections. Borehole evidence is very limited, with very few boreholes reaching more than a few hundred metres in depth, and none constraining the boundaries of formations within the Early Devonian.

Rock type descriptions

There are three principal outcrop areas for Early Devonian rocks in the region: north Devon; north Cornwall–south Devon, and south Cornwall.

North Devon

The Early Devonian in North Devon is represented at outcrop principally by the Lynton Formation (or 'Lynton Slates'), which comprises mainly pale greenish-grey mudstone with common siltstone (overall fining downwards), hence a HSR PRTI. It outcrops at Lynton on the North Devon coastline and extends about 10 km inland from there into Exmoor, in a belt about 2 km wide. It also crops out in a narrow strip on the south-west side of the Quantock Hills.

The Lynton Formation forms the outcropping upper part of a sequence of Early Devonian rocks that occur widely in the depth range of interest in these areas. Limited lithological information is available (e.g. from boreholes) for the concealed parts of the sequence. A broad west-north-west-trending anticlinal structure (the Quantock Anticline), extending through Lynton inland towards the south of Bridgwater, brings these Early Devonian rocks into the depth range of interest in a broad zone beneath much of the Exmoor area (largely concealed by younger rocks). This zone extends northwards of a line between Ilfracombe and the south side of the Quantock Hills (where the Early Devonian rocks are faulted down to the south below the depth range of interest), and northwards towards the Bridgwater area (again where the Early Devonian rocks are truncated by faulting). The Early Devonian rocks descend below the lower limit of the depth range of interest to the east of Taunton, due partly to the eastwards plunge of the anticlinal structure and an increasing thickness of Mesozoic cover. A southerly dip away from the Quantock Anticline takes the Early Devonian rocks below the depth range of interest south of the line from Ilfracombe to the south side of the Quantock Hills; they remain below the depth range of interest for the whole of the central Devon (Culm basin) area.

North Cornwall–south Devon

Early Devonian rocks occur at outcrop across north Cornwall and south Devon, from between Padstow and Perranporth on the west coast to between Torquay and Start Point on the east coast. The sequences reach up to 5000 m in total thickness (Leveridge and Hartley, 2006), and divide broadly into the following groups, described in descending stratigraphical order.

The Meadfoot Group is divided into two units. The upper unit, formalised as the Staddon Formation, principally comprises medium to thick beds of fine to medium-grained sandstone with thin interbedded mudstones and siltstone, and hence is not considered a PRTI. This formation reaches 400–500 m thickness, although the upper and lower boundaries are thrust-faulted (the latter over Mid Devonian rocks to the north). This formation forms about a 3 km-wide outcrop fringing the whole northern edge of the Early Devonian outcrop, where it consistently forms the upper part of the sequence.

The lower (and larger) part of the Meadfoot Group is generally not divided into formations ('Meadfoot Group' in Waters et al., 2015) and is described as comprising dominantly dark shales and siltstones (hence a PRTI) with sporadic grey-brown sandstones and shelly beds (BGS Lexicon). However, in parts of the east of the north Cornwall–south Devon outcrop area, the whole thickness of this succession (underlying the Staddon Formation and overlying Dartmouth Group) is designated as the Bovisand Formation. This includes a 2 km-wide (cross strike, north–south) outcrop extending inland from the east Devon coast just south of Brixham, past Dartmouth, and a faulted, 5 km-wide outcrop extending westwards from Plymouth to the south of Liskeard (BGS DiGMapGB50). Here the Bovisand Formation is described as dominantly slaty mudstone (hence a PRTI) with thin sandstone beds and sporadic limestone beds. It is estimated to be at least 1300 m thick, although this is a structural thickness between thrust-faulted upper (against the Staddon Formation) and lower (against the Dartmouth Group) boundaries (BGS Lexicon). The Meadfoot Group is extensively thermally metamorphosed (hornfelsed) in 1 to 3 km-wide zones (aureoles) around the St Austell granite (between the towns of St Austell and Bodmin).

The Dartmouth Group (Early Devonian) is generally undivided on BGS mapping, and described as dominantly mudstone (hence an HSR PRTI) with some siltstone and sandstone laminae and beds up to 0.5 m thick, intercalated in places with volcanic rocks including basalt and tuff (BGS Lexicon). The lower boundary is thrusted (e.g. in the Plymouth area, over the younger Bovisand Formation) and the thickness is estimated at up to 3300 m (BGS Lexicon).

For the north Cornwall and south Devon area, the lower mudstone-dominated part of the Meadfoot Group and the underlying Dartmouth Group can be considered together as constituting the Early Devonian PRTI. In terms of occurrence within the depth range of interest, the following observations can be made regarding these combined Early Devonian PRTIs.

- The significant combined thickness (in the order of 4.5 km) means that they will occur within the depth range of interest beneath much of the described outcrop area.
- The St Austell granite occupies a significant area within the outcrop of the Meadfoot Group, and modelled shallow dips of the granite contact on its northern side. Therefore granite may be encountered within the depth range of interest beneath the Meadfoot Group metasediments in a 7 km-wide zone around the northern part of the pluton, extending towards Bodmin. This corresponds approximately with the mapped area of hornfelsed sediments around the pluton (which in themselves are the evidence, in the absence of any deep borehole information, for modelling granite at a relative shallow depth).
- A potential connection at depth between the St Austell and Bodmin granite plutons means that the Meadfoot Group in this area (including where it is overlain in the northern part by Mid Devonian rocks) effectively occupies a synclinal form within the depth range of interest but is underlain by granite at relatively shallow depth, potentially within the depth range of interest.
- To the west of the influence of the St Austell and Bodmin granite plutons, the Meadfoot Group PRTI occurs within the depth range of interest beneath its outcrop area, but is dropped to the lower part of the depth range of interest as it crosses the north-directed (southerly inclined) thrust running along the northern margin of the Early Devonian outcrop (at surface this thrusts the Staddon Formation over Mid Devonian rocks). It then remains in the depth range of interest for a broad swathe to the north of this thrust line, extending as far north as a west–east line through Padstow.
- In east Devon, a similar situation occurs, with the northern margin of the Early Devonian being marked by a north-directed thrust (thrusting the Staddon Formation over Mid Devonian rocks), to the north of which the Early Devonian PRTI drops to the middle to lower part of the depth range of interest. This means in east Devon, the PRTIs occupy the depth range of interest not only beneath much of their outcrop area (i.e. southwards as far as Salcombe) but also in a broad belt extending up to 6 km to its north beneath Mid Devonian rocks, as far as a west–east line passing through Ivybridge and St Ives (where a further north-directed thrust reduces it to below the depth range of interest).
- To the south of the main outcrop area, the Early Devonian PRTIs continue to occupy much of the depth range of interest beneath Mid Devonian rocks for around a 10 km-wide swathe extending as far as a north-west to south-east line between Redruth and Falmouth.

South Cornwall

Early Devonian rocks are also modelled (through extrapolation from surface mapping and not constrained by borehole information) to continue at depth further south in Cornwall, concealed beneath Mid Devonian rocks. However, due to lack of direct lithological data from borehole provings, it is uncertain whether these would form PRTIs, although comparison to similar age rocks further north (e.g. in north Cornwall) suggests they could.

Early Devonian rocks occur in the lower part of the depth range of interest beneath Mid Devonian rocks in a broad (5 km across strike) thrust slice between the north-directed Dodman Thrust (forming the northern margin of the Lizard Complex) and the Carrick Thrust (running west-south-west between Porthleven and Falmouth).

Early Devonian rocks also occur in the lowest part of the depth range of interest, beneath Mid Devonian rocks in a restricted area approximating to a 3 km radius around Penzance.

4.2.2.7 UNNAMED DEVONIAN IGNEOUS INTRUSION — HSR

This comprises the bulk of the Lizard ophiolite, and, together with the underlying Devonian hornblende schists and mica schists (a PRTI described in Section 4.2.2.6), makes up the bulk of the wider Devonian Lizard Complex (Cook et al., 2002; Leveridge and Hartley, 2006). Together, they represent HSR PRTIs, related to their igneous origin.

The term ‘unnamed igneous intrusion, Devonian’ (UIID) comes from Waters et al. (2015). However, although the rocks are considered igneous in origin, they are not as a whole intrusive, but instead represent components of an ophiolite emplaced by north-west directed thrusting (Kirby, 1979; Cook et al., 2002; Leveridge and Shail, 2011). They comprise metamorphosed and deformed mantle units (e.g. serpentinised peridotites), crustal units (including gabbros, dykes and amphibolites), with some subsidiary later syndeformational intrusions.

The overall structure of these rocks is therefore one of thrust sheets, likely to be only several hundred metres in structural thickness (Leveridge and Hartley, 2006; Leveridge and Shail, 2011), emplaced by north-west-directed, early Carboniferous Variscan thrusting over related sea-floor sediments and ocean-floor basalts, represented by the Old Lizard Head Series and the Landewednack Hornblende-Schist. The latter comprise undivided Devonian hornblende schists, another of the PRTIs (see Section 4.2.2.6). The latter are variously considered in the literature to be part of the ophiolite itself.

The Predannack Downs borehole (Figure 3) confirms this interpretation, proving some 298 m of UIID overlying hornblende schists ascribed to the Devonian rocks described in Section 4.2.2.6. The UIID rocks only just reach the upper part of the depth range of interest in the Lizard area.

Principal information sources

Information on the thickness and lithology of the Devonian sequences of the Lizard Complex comes principally from surface outcrop mapping, in particular from coastal exposures around the Lizard peninsula. These are described in various publications and form the basis for the NGS3D model and cross-sections. Borehole evidence is limited, although the Predannack Downs borehole above provides useful thickness information regarding the Lizard sequences.

4.2.2.8 UNDIVIDED DEVONIAN ROCKS: HORNBLENDE SCHIST/MICA SCHIST; UNDIVIDED EARLY PALAEOZOIC ROCKS — HSR

These units form the structurally lower part of the Lizard Complex, beneath the unnamed igneous intrusive rocks above. Devonian hornblende schists, along with Devonian mica schists, also make up the Start Complex at Salcombe on the south coast; the Start Complex is described as originating as oceanic floor rock sequences and correlated with the Lizard Complex by Floyd et al. (1993). Correlation of the Start Complex units with the lower tectonic units of the Lizard Complex is also suggested by Leveridge and Hartley (2006), based on their flyschoid-like appearance and tectonic level. These rocks occur at outcrop and across the full range of the depth range of interest beneath much of the Lizard peninsula. They also occur across the depth range of interest beneath Start Point and offshore the south.

The structurally lowest and oldest rocks in the Lizard Complex are represented by metamorphic rocks exposed in the south-west of the Lizard, including the Man of War Gneiss, with an implied Ordovician age (Cook et al., 2002; Leveridge and Shail, 2011). These have a very limited outcrop area but are shown in the NGS3D to be of the order of 800 m thick and occur within the lower part of the depth range of interest at approximately 1000 to 2000 m beneath much of the Lizard region, overlying early Palaeozoic rocks. The latter are also a HSR PRTI, but beneath the onshore area of the Lizard they mostly occur below the depth range of interest. They do, however, rise through the depth range of interest to crop out further offshore to the south of the Lizard (Waters et al., 2015).

Principal information sources

Information on the thickness and lithology of the Devonian sequences of the Lizard Complex comes principally from surface outcrop mapping, in particular, from coastal exposures around the Lizard peninsula. These are described in various publications and form the basis for the NGS3D model and cross-sections. Borehole evidence is limited, although the Predannack Downs borehole (described in Section 4.2.2.7) provides useful thickness information regarding the Lizard sequences, constraining the upper contact of the Devonian hornblende schist unit.

4.2.2.9 UNDIVIDED DEVONIAN ROCKS — HSR

This classification is used in the offshore area for rocks of inferred Devonian age. These rocks occur at (seabed) outcrop offshore south of the Lizard peninsula, and west of Land’s End, and also in the subsurface offshore of north Devon. The Devonian rocks are shown in the NGS3D as occurring across the depth range of interest in all these areas.

Principal information sources

Information regarding these offshore sequences comes exclusively from subsurface BGS seismic interpretations, and extrapolation from the published BGS 1:250 000-scale offshore bedrock mapping.

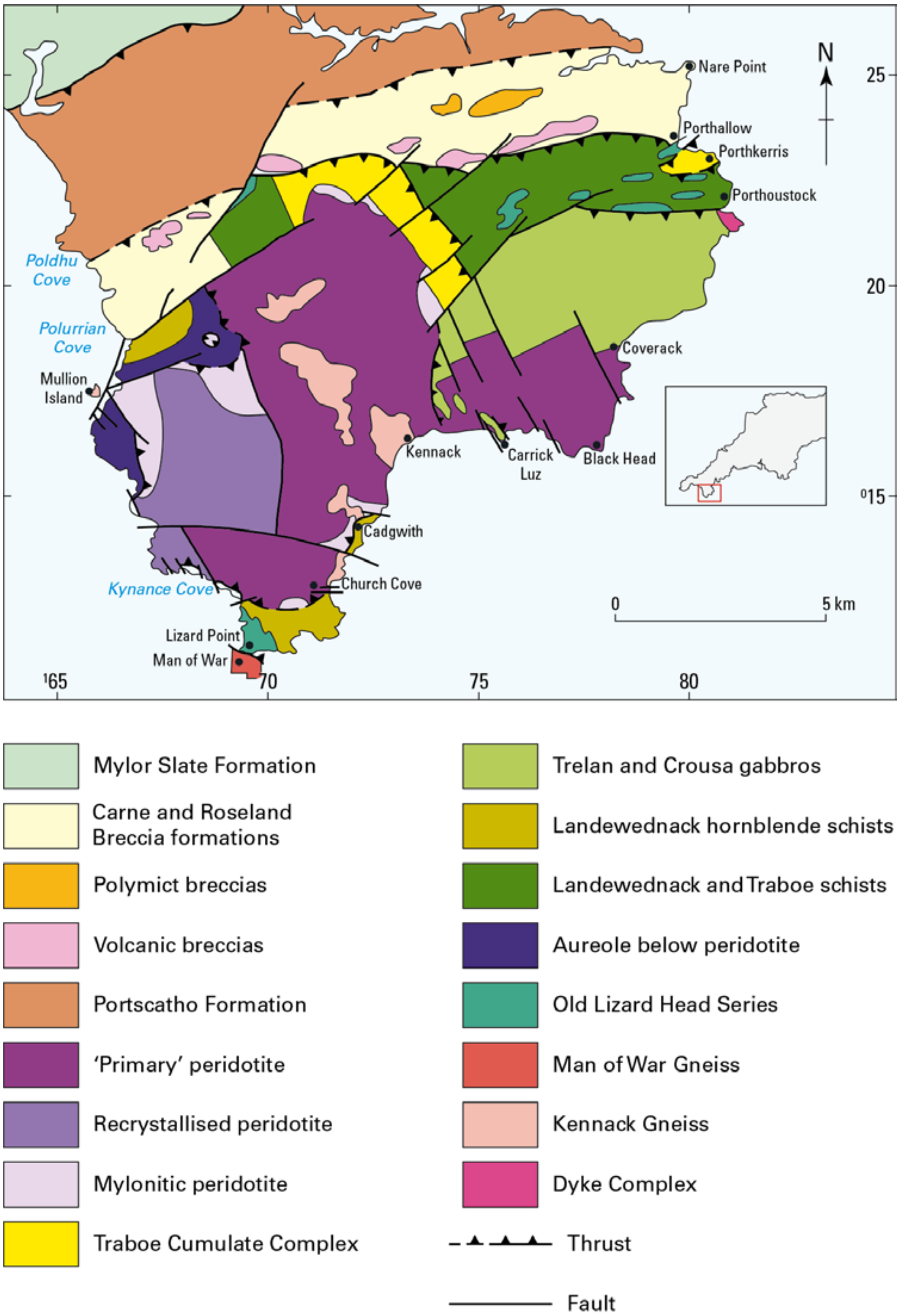

Figure 26 Sketch map of the Lizard peninsula showing the divisions of the Lizard Complex and its relationship with the lithostratigraphical units of the Gramscatho Group. After Cook et al (2002). © Cambridge University Press

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

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

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

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

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

Faulting in the UK is pervasive and therefore it is not practical to identify all faults and fault zones. Although any faulting can result in an area being difficult to characterise and could influence groundwater movement, it is assumed that minor faulting will be characterised in detail at the GDF siting stage and therefore only major faults 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 South-west England region lies within the Variscan orogenic belt, which runs across southern England and small areas of southern Wales and Ireland, and across extensive areas of Europe. The South-west England region forms part of the Rhenohercynian Zone, and is contiguous with the rocks of this zone in

Belgium and Germany (Holder and Leveridge, 1986a), interpreted as oceanic collision belts (see Franke, 1989).

The sedimentary rocks of Devonian and Carboniferous age were deposited in fault-bounded basins (Figures 17 and 18), which are recognised as forming part of a passive margin sequence (Holder and Leveridge, 1994). The correlation of these rocks across north-western Europe (Holder and Leveridge, 1986a) suggests a pattern of extensive east–west-trending sedimentary basins forming the northern passive margin of a laterally extensive Rhenohercynian oceanic basin (Franke, 1989). Oceanic remnants and active margin sequences from this basin are preserved in southern Cornwall as the Lizard ophiolite. The sequence of extension and basin opening followed by inversion and deformation within the Variscan rocks of the South-west England region is related to the continental rifting and growth of the Rhenohercynian Ocean, followed by its closure during continental collision.

Rifting of the passive margin occurred over a period of approximately 65 million years, from the Early Devonian to the early Carboniferous, with extensional faulting getting progressively younger northwards (Leveridge et al., 2002) as shown in Figure 27. Thermal subsidence associated with the post-rifting stages of ocean spreading (Bott, 1992) was not completed before continental collision occurred with inversion in the Gramscatho basin (Holder and Leveridge, 1986b) and the subsidence of the Culm basin occurring contemporaneously.

Deformation of the Rhenohercynian passive margin rocks was related to the latest of several continental collision events within the Variscan deformation belt of southern and central Europe (see Holder and Leveridge, 1994). Collision-related deformation progressed northwards with time by a process of inversion, out-thrusting of basin fill on basin margin faults, and deformation, which continued until the basin-bounding faults locked and stress could be transmitted to the next basin. This style of ‘soft’ deformation compartmentalised compressive stresses, allowing extension and sedimentation to proceed in the north of the district as basins to the south were being inverted and deformed in compression. The collision-related deformation was therefore a relatively slow and continuous process which spanned approximately 50 million years, becoming diachronously younger northwards (Leveridge et al., 2002).

The Rhenohercynian passive margin sequence within the South-west England region consists of six major east–west-trending fault-bounded basins: the Gramscatho, Looe, south Devon, Tavy, Culm and north Devon basins, together with the intervening highs (Figure 27). The synrift basin fill of the Gramscatho basin is mostly covered by subsequent Late Devonian synconvergence sedimentation. To the north the Looe basin is overthrust to the south by sediments of the Gramscatho basin (Holder and Leveridge, 1986b). Its northern boundary is defined by the interbasinal high deposits of the Plymouth Limestone Formation (Leveridge et al., 2002). The strata of the Looe basin constitute three major thrust nappes. At each thrust front, large-scale antiformal folding is present in the hanging wall, which suggests that internally the Looe basin comprised three sub-basins with half-graben geometries.

The south Devon basin was constrained to the south during the Devonian by platform carbonates on an ‘outer shelf’, and to the north, at the edge of an ‘inner shelf’, by volcanics associated with the marginal fault of a half-graben (Selwood, 1990). The south Devon basin formed by rotational faulting on its northern boundary during the Eifelian. It was a half-graben basin and the southern edge of the rotated fault block formed a linear structural high (the ‘Plymouth high’) separating the south Devon basin from the Looe basin to the south. The Plymouth high is now represented in two relatively thin thrust slices that make up the Plymouth Limestone Formation. The limestone associated with this interbasin high extends across south Devon to Torbay. In the west, increased northward displacement on the out-of-sequence thrust bounding the Staddon Formation has obscured the Plymouth Limestone Formation beneath the overthrust sedimentary fill of the Looe basin.

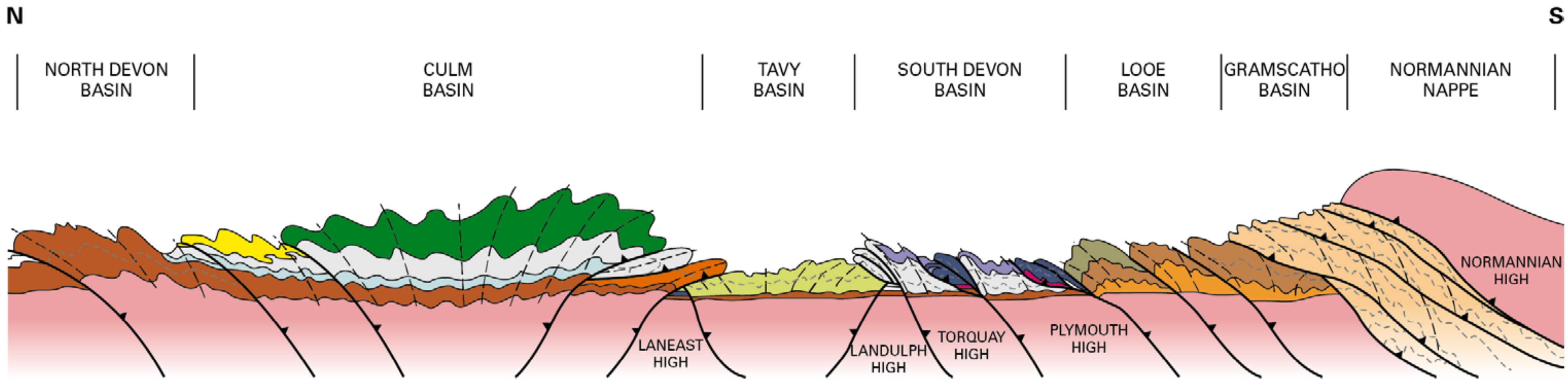

Figure 27 Sketch cross-section of the Variscan belt of South-west England, late Carboniferous. The sequence comprises six major east–west-trending fault-bounded basins: the Gramscatho, Looe, south Devon, Tavy, Culm and north Devon basins, with extensional faulting and intervening highs, getting progressively younger northwards. British Geological Survey © UKRI 2018

The formation of the Tavy basin to the north of the south Devon basin by continued regional extension was initiated in the Frasnian and continued into the earliest Tournaisian (Leveridge et al., 2002). The southern margin of the Tavy basin is now concealed beneath thrust sheets derived from the northern edge of the south Devon basin, but it originally lay to the north of the Landulph high. Much of the Tavy basin is overlain by southerly directed thrust sheets originating on the southern margin of the Culm basin. The pre-Variscan deformation width of the Tavy basin is estimated at least 22 km (Leveridge et al., 2002). The distribution of Tavy Formation facies as an east–west-trending belt across South-west England suggests an east–west trend to the Tavy basin that was controlled by east–west-trending extensional faults formed on the passive margin similar to the south Devon and Looe basins to the south. The southerly vergence of structures in most of the rocks of the Tavy basin and the northerly vergence of deformation structures near its northern boundary (Isaac et al., 1982) suggests a symmetrical graben basin geometry.

The Culm basin, lying to the north of the Tavy basin, began to develop in the Tournaisian. The bulk of the Culm basin fill indicates that the basin, in the Late Carboniferous, had an east–west trend (Thomas, 1988). The opposed vergence of the deformation structures in the Culm rocks, northwards on the northern margin of the basin and southwards on the southern margin (Dearrman, 1971), indicates that the basin geometry was generally symmetrical. In its early stages, subsidence of the basin was fault controlled with the form of a symmetrical graben. The Culm basin originated in the extensional regime and later became a foreland basin (Hartley and Warr, 1990). After deformation the Culm basin is some 50 km in width, considerably larger than the Devonian-aged basins.

The nature and extent of the north Devon basin, unlike the passive margin rift basins to the south, is not well constrained. The basin succession, unlike those of the southern basins, is relatively straightforward without major repetition by thrust faulting (Edmonds and Williams, 1985). It is deformed by gently plunging upright to northward-verging minor and major east–west folds (Sanderson and Dearman, 1973) and an associated axial plane slaty cleavage, which is locally intense, transposing sedimentary features and fossils (Whittaker and Leveridge, 2011).

A consequence of the fill of each of the Early Devonian sub-basins being expelled northwards over its neighbour is the transformation of each bounding rift fault into a basal thrust or the development of a short-cut footwall thrust, and the development of an associated major hanging-wall anticline (Leveridge et al., 2002). The juxtaposition of similar-aged deposits by the thrusting is a function of the extent of the inversion. The geometry and vergence of structures is a function of the reactivation of former extensional faults. In the cases of the Tavy and Culm basins, which are interpreted to be full-graben complexes, the southerly vergence and facing of major structures represents a primary northerly inclination of basinal faults rather than backfolding during inversion uplift (Leveridge et al., 2002). The northerly vergence at the southern margin of the Tavy basin is a probable consequence of the immediately preceding overthrusting from the south (Leveridge et al., 2002).

By late Visean to earliest Namurian times, all of the sedimentary basins to the south of the Culm basin were inverted, with inversion of the Culm basin initiated in the Namurian (Leveridge et al., 2002). The southern margin deposits were thrust southwards out of the Culm basin, with the development of a major southerly facing, overturned, antiformal fold.

The second compressive phase of deformation, at the end of the Westphalian, effected completion of the uplift and deformation of all the basin deposits (Leveridge et al., 2002). As the second compressive phase had a north-west to south-east maximum principal stress, oblique to the east–west trend of the primary basin, structures in the late Carboniferous rocks and on the northern margin of the basin reflect transpressive deformation (Leveridge et al., 2002). This major cumulative uplift and southerly out-thrusting of the southern part of the basin fill, and the subsequent gravitational collapse of the edifice produced, is interpreted to be responsible for the complex southern margin of the Culm basin (Leveridge et al., 2002). The second compressive phase of deformation to the south, apart from causing the development of folds, also produced the out-of-sequence thrusting and reactivation of the strike-slip faults that had developed to the south during first phase of compressive deformation, probably when basins had locked up (Leveridge et al., 2002). A third phase of deformation, towards the end of the Carboniferous, resulted in southward-verging structures and possible correlatives of the southerly directed thrusting of the Culm basin rocks during the collapse of the uplifted basin and the early phase of late 'extensional' movements on first and second phases of thrusts (Leveridge et al., 2002).

The latest stages of the Carboniferous and the Permian are marked by a number of tectonic events related to a post-Variscan phase of regional extension (Holder and Leveridge, 1994). Uplift and extension initiated around 298 and 290 Ma with the intrusion of lamprophyric magma into east–west-trending fractures (Rundle, 1980). Extension and pressure release lead to the melting of the lower crust–mantle boundary and the intrusion of the Dartmoor and Bodmin granites between 290 and 280 Ma (Darbyshire and Shepherd, 1985; Chen et al., 1993; Chesley et al., 1993). Related acid volcanic activity along the main north-west-trending strike-slip faults, including the associated high-level Elvan intrusion, and the intrusion of similar felsitic magma into east–west fractures, is compatible with north–south extension at the time. Similarly the formation of the east–west-trending, main stage, mineral veins, dated at 280 ± 20 Ma (Moorbath, 1962), indicates that the crust was undergoing north–south extension. The magnitude of this latest Carboniferous to Permian extension is indicated by the formation of sedimentary basins, with several kilometres' thickness of Permian sediments, above extensionally reactivated Variscan thrusts in Plymouth Bay (Evans, 1990), the Haig Fras, Melville and St Marys basins in the South-west Approaches (as shown on Figure 28) (Hillis and Chapman, 1992), and the Crediton trough in Devon (Durrance, 1985). Within the South-west England region, a number of gently dipping thrusts exhibit significant extensional reactivation, most of which can be ascribed to Permian extension.

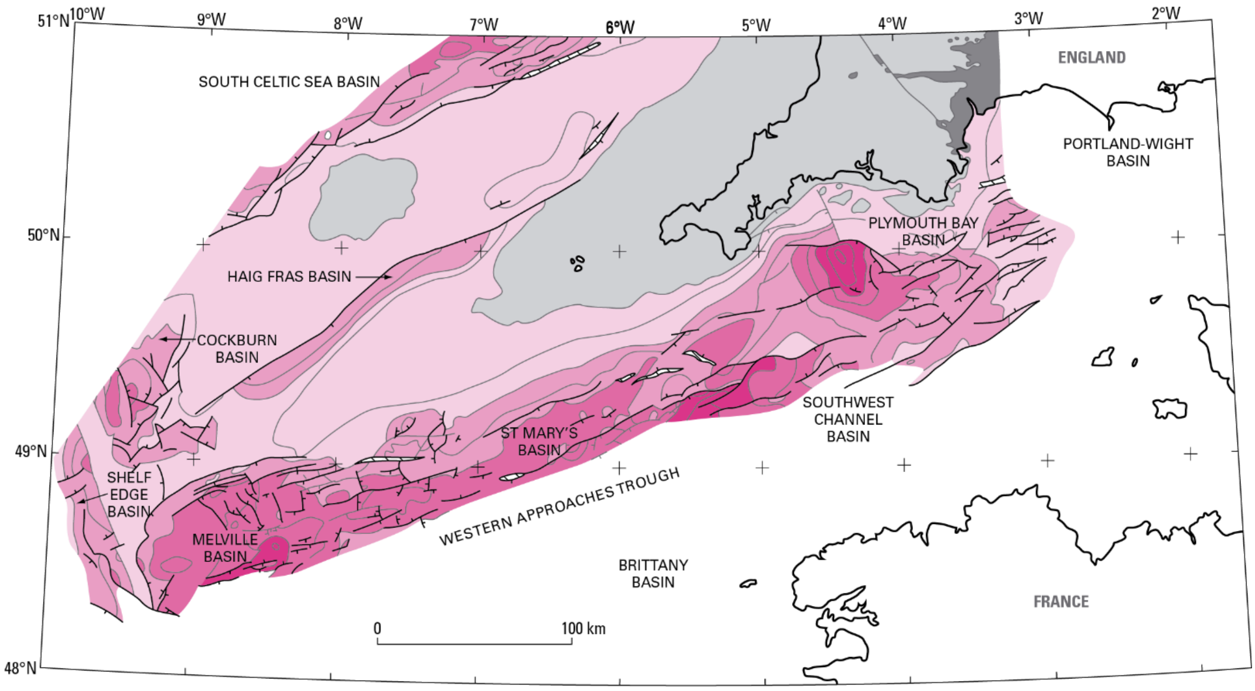

Figure 28 Distribution of the preserved Permo-Triassic rocks in the south-west of the region showing contours of depth to the base of preserved Permian rocks. Contours are at 1000 m intervals from 0 m (lightest pink) to > 4000 m (darkest pink). British Geological Survey © UKRI 2018

The Late Permian to Cretaceous was marked by a period of general subsidence. Palaeogene deposits occupying the low-lying ground of the Bovey basin (Selwood et al., 1984), together with a regular and continuous series of sea-level retreat features, indicate the progressive emergence of the South-west England region from Cretaceous to Holocene times.

Post-Variscan movements include sinistral fault displacements on the north-west-trending faults during north–south extension in the Permian, the Late Triassic to Jurassic or the early Palaeogene. The dextral displacements of the north-west-trending faults are related to north–south compression most probably of Late Cretaceous, late Palaeogene–Neogene or Miocene age (Leveridge et al., 2002).

5.3 MAJOR FAULTS

The major faults selected from analysis of the UK3D model and facies relationships in the region (Figure 29) exhibit a variety of orientations and evolutionary histories as a consequence of the complex Palaeozoic to Cenozoic structural history, described in Pharaoh and Haslam (2018). Their presence affected sedimentation in Devonian to Permian and later times and also controlled the position and alignment of folds and faults visible at the surface.

The introduction established the complex tectonic background of the region and long history of fault reactivation. However, the major faults can be grouped into three categories based on their orientation, which was directly controlled by the principal stress direction during formation and in later phases of fault reactivation:

- north-east-trending structures
- east-trending structures
- north-west-trending structures

This grouping approximately correlates with the age of faulting with the oldest being described first.

5.3.1 North-east-trending faults

The north-east-trending fault zone consists of a series of thrust stacks that developed during the Mid to Late Devonian including the Lizard, Dodman, Veryan and Carrick thrusts. The Lizard–Dodman–Start Thrust emplaced the Lizard ophiolite and its sole over the southernmost Gramscatho basin. Day and Edwards (1983) shows a separate thrust accounting for the Dodman rocks and joining the Lizard Thrust east of the peninsula, however, a single fault is assumed here due to the sparse seismic correlation in Plymouth Bay. The thrust dips gently (about 35º) southwards, downthrowing to the north, and has an arcuate east–west trend (Edwards et al., 1989). The thrusts occur mostly in the offshore region where they have been interpreted from seismic data (Edwards et al., 1989). There is no information on the amount of displacement on this thrust.

The Veryan Thrust is structurally below the Lizard–Dodman–Start Thrust and above the Carrick Thrust onshore. The Veryan Thrust dips to the south and downthrows to the north, with an undulating, approximately east–west trend. The thrust juxtaposes the Pendower Formation against Portscatho Formation.

The Carrick Thrust lies below the Veryan and Lizard–Dodman–Start thrusts, both onshore and offshore. It was imaged on a seismic profile ending about 6 km south of Dodman Point, where it was calculated as nearly 4 km deep, but emerging onshore, north of the point (Edwards et al., 1989). It is either intruded by granite, or the granite has resisted its northward advance, a Late Devonian age for the thrust suggesting the former is true (Holder and Leveridge, 1986b). The thrust dips to the south and downthrows to the north with horizontal displacement in excess of 10 km and has an arcuate east–west trend. The thrust juxtaposes the Portscatho Formation against the Gramscatho Group.

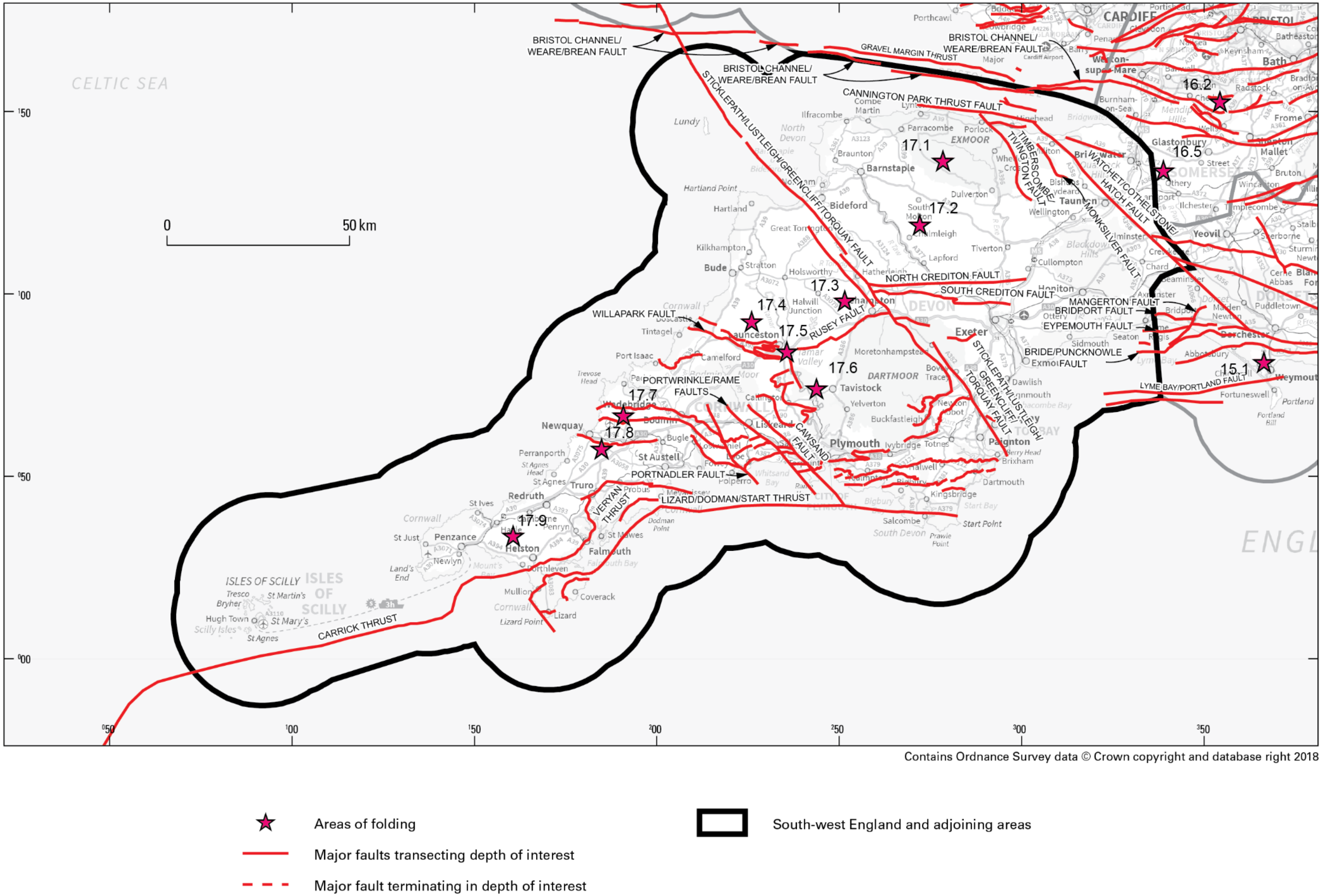

Figure 29 Major faults and areas of folding in the South-west England region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

5.3.2 East-trending faults

East-trending faults are typically Devonian to Permian in age and reflect the underlying Early to Mid Devonian extensional structural control. The main east-trending faults are associated with changes of stratigraphy across the fault, which has led to the interpretation of the faults as basin-bounding normal faults on a passive margin during the Devonian. During the Late Devonian and Carboniferous these structures formed lines of weakness and were reversed resulting in the expulsion of the basin sediments and the propagation of reverse faults and thrusts onto the basin margins.

The Bristol Channel Thrust is clearly traceable on seismic sections from offshore areas north of Somerset to the outer Bristol Channel north of Lundy, at 2–4 km depth. It has a west-north-west strike and a gentle to moderate south-south-west dip of 24–31º (Miliorizos et al., 2004). The upward continuation of the Bristol Channel Thrust is a normal fault, the Bristol Channel Fault, intersecting the seabed. The fault shows a normal, southerly downthrow juxtaposing Late Jurassic units in the footwall and hanging wall across the inner Bristol Channel (Miliorizos et al., 2004).

The Cannington Park Thrust is inferred between several closely spaced, small inliers north of the Quantock Hills exposing Carboniferous and Devonian strata (Anderson and Owen, 1968) and extends into the offshore north of the Devon coast (Edwards, 1999). It is not mapped farther west, but is likely to be present. The fault trends east–west and dips to the south with a throw in excess of 2 km juxtaposing Devonian over Carboniferous Limestone both at Cannington (onshore) and offshore (Edwards, 1999).

The Culm basin is postulated to be fault controlled at its northern and southern margins, although a major fault on the northern margin has not been proved. Faulting on the southern margin consists of a complex zone of thrusting and faulting, up to 20 km wide, where Carboniferous rocks of the Culm basin have been expelled southwards over the Devonian of the Tavy basin. The major thrusts are typically gently dipping to the north, trend approximately east–west, and are over 70 km in mapped length. The faults include the Rusey Fault, which is exposed on the coast between Tintagel and Boscastle. This is composed of highly disturbed dark shales, siltstones and sandstones, overlying a rust-stained breccia made up of crushed fragments of quartz, sandstone and siltstone. The fault zone and breccia dip 35º north-east, the north-westerly trend of the fault being due to the influence of a dextral wrench fault trending north-west (McKeown, 1973).

The Willapark Fault lies south of and runs parallel to the Rusey Fault and probably has a similar tectonic and structural history, however, little is known about this fault except for small observation on the coastal section between Boscastle and Tintagel.

The fault zones are cut both by the dextral north-west trending wrench fault and by steep, normal, east-south-east-trending faults (McKeown, 1973). In coastal cliff sections the wrench fault and steep normal faults produce repetition of the Rusey low-angle fault.

The Culm basin is characterised by extensive folding of interbedded mudstones, sandstones and siltstones. The folding varies from being recumbent and south-facing in the south of the basin to upright and tight through the centre, fanning to north facing in the north of the basin (McKeown, 1973).

The Permian–Triassic Crediton and Tiverton basins impinge form the east through the centre of the Culm basin. The Crediton basin is an east-trending, Permian, mainly half-graben some 45 km long and 6 km wide with an estimated depth of between 0.7 to 0.9 km (Davey, 1981; Cornwell et al., 1992). The detailed subsurface geometry of the basin is uncertain as no boreholes penetrate basement within the trough and seismic evidence is lacking. The position of the Crediton trough coincides with that of the boundary between the Carboniferous Crackington and Bude formations; Durrance (1985) proposes that the trough resulted from reversed (extensional) reactivation of a south-dipping Variscan thrust on which the Crackington Formation had previously been displaced northwards over the younger Bude Formation. Southerly downthrowing normal faults are present along the north side of the Crediton trough (Davey, 1981); on the south side, the trough is bounded by an east-trending normal fault with a northerly downthrow of up to 0.9 km.

The northern margin of the Looe basin and southern margin of the south Devon basin are proposed to be controlled by extensional faults at depth, which formed on the passive margin and controlled sedimentation (Leveridge et al., 2002). As the Devonian and Carboniferous compression progressed northwards across the South-west England region, basins were inverted and the shortcut thrusts formed above the earlier, basin-bounding normal faults. The thrusts trend to the east and typically dip to the south and throw to the north.

The major faults consist of at least three main unnamed thrusts forming a zone of deformation approximately 10–20 km wide towards the northern margin of the Looe basin (Leveridge et al., 2002).

A structural line termed the Start–Perranporth line has been proposed across the south of the Looe basin and is marked as a zone with changing confrontation in cleavage, however, this has not been proved as a fault and is therefore not included in this report. Folding in the Looe basin is recumbent and tight, facing southwards (Leveridge et al., 2002).

5.3.3 North-west-trending structures

A major feature of the region is the oblique dextral strike-slip faulting, striking between north-west and north-north-west, which is associated locally with a subordinate complementary fault set striking between north-north-east and north-east. Most notable is the Sticklepath Fault, which traverses the peninsula and has a residual dextral offset of 5 km at Torquay (Leveridge et al., 2002). The Cawsand and Portwrinkle faults have similar and greater residual offsets, respectively, as illustrated by the displacement of lithostratigraphical units of the Looe basin to the west of Plymouth. The Watchet–Cothelstone–Hatch Fault along the south-west side of the Quantock Hills dextrally displaces rocks of the north Devon basin by up to 15 km (Leveridge et al., 2002). Cumulative vertical movements of up to a few hundred metres are also evident on these major faults. Although Devonian (as well as Cenozoic) origins have been proposed there is no good evidence to indicate that such faults influenced depositional environments before the Pennsylvanian.

The north-west-trending faults are part of a wide family of structures across the Variscan belt along which associated ductile tectonic reworking has been dated at approximately 321 Ma (Matte, 1986). Near Plymouth, the faulting appears to have developed at the same time as the first compressional folding (Leveridge et al., 2002). Major fault zone fabrics indicate a complex movement history, with phases of not only dextral but also sinistral displacements.

The Watchet–Cothelstone–Hatch Fault transects the north-east part of the region and separates the Quantock Hills from the main Exmoor Devonian outcrop, and is traceable for at least 34 km. It is postulated to cross the Bristol Channel via the Watchet Fault and link to the east-trending faults of the Wessex basin to the south-east. This fault crops out along the Bristol Channel intertidal zone. It dips 55 degrees south-west (Whittaker, 1972) with about 275 m of dextral post-Early Jurassic slip. The stratigraphical throw juxtaposes Early Jurassic Lias Group against Triassic Mercia Mudstone Group. The fault has a vertical displacement of 55 m and downthrows to the north-east, so is here a reverse fault. However, there is still much debate as to the northern and southern extension of the fault. It is a normal fault on the foreshore near Watchet, and by the offset of Devonian stratigraphical boundaries to the south, also strike slip. The fault has an offset of 14–16 km dextrally, based on Devonian markers and late Variscan fold axes (Miliorizos and Ruffell, 1998). The Hatch segment of the fault offsets the Penarth Group escarpment by 2.5 km (Whittaker, 1972). The downthrow to the south-west is probably about 200 m, but not constrained either by boreholes or seismic data. The fault truncates east and west-north-west-trending faults and causes dextral drag of their traces as seen in the vicinity of Ilminster.

The Sticklepath–Lustleigh–Greencliff–Torquay Fault forms a series of left-stepping *en échelon* faults (Holloway and Chadwick, 1986). The fault trends north-west with unknown dip. There is no seismic data across this fault onshore. The Lustleigh Fault segment lies on the west of the Bovey basin. From gravity data, it has been modelled as dipping up to 63° to the north-east (Fasham, 1971). The fault is associated with the formation of Cenozoic basins along its length (the Stanley Bank basin in the Bristol Channel, and the Petrockstowe and Bovey basins), which formed during sinistral strike-slip displacement (Holloway and Chadwick, 1986). The dextral initiation of the fault was probably of late Variscan origin offsetting an earlier east–west-orientated Variscan thrust by up to 10 km (Holloway and Chadwick, 1986). Some of the associated strike-slip faults are traced by lines of springs at the surface. Displacement occurred both before and after deposition of Palaeogene sediments in the Petrockstowe basin where subsidence occurred in a graben (Freshney et al., 1979) due to the overlapping left stepping of the Sticklepath Fault segment and Greencliff Fault segment. In the Bristol Channel the fault downthrow is to the north-east (Devonian against Cenozoic). The stratigraphical offset varies between the Cenozoic, Permian, Carboniferous and the Dartmoor granite. Horizontal dextral displacement is recorded as 4.8 km (Crackington and Bude formations), 1.3 km (south Dartmoor) and 2 km (Crediton–Hatherleigh) by Holloway and Chadwick (1986).

The Timberscombe–Tivington Fault runs parallel to the Watchet–Cothelstone Fault and bounds the small Triassic Porlock basin in the north of the region, west of Minehead. The fault trends north-west with a dip of between 60º and vertical (Webby, 1965). The Variscan dextral strike-slip displacement is estimated to be in the order of 2 km (Miliorizos and Ruffel, 1998) with Cenozoic displacement on the fault possible. The Timberscombe–Tivington Fault of Webby (1965) consists of two subparallel faults about 0.5 km apart. The movement on these faults has both dextral transcurrent and vertical components; the vertical downthrow across the system was estimated to be 427 m and the amount of dextral displacement about 1.4 km (Webby, 1965).

The Monksilver Fault is approximately 8 km east of, and approximately parallel to, the Timberscombe Fault. The fault has a mapped length of approximately 30 km and offsets Devonian and Permian strata. The fault is interpreted as vertical with an estimated normal throw of 630 m to the east in UK3D.

The Cawsand, Portwrinkle–Rame and Portnadler faults are parallel, north-west to north-north-west-striking faults near Plymouth. These faults have dextral offsets of the order of 4 km, 7.5 km (with up to 2 km on the Rame Fault segment) and 1.5 km respectively (Leveridge et al., 2002). Fault breccias are up to 2 m wide, as in the case of the Portwrinkle–Rame Fault, which comprises 0.5 m of clay gouge and 1.5 m of intensively sheared country rock (Leveridge et al., 2002). Rotation of bedding over several tens of metres adjacent to the faults and drag on subordinate subparallel faults indicate that the major movements have been dextral strike slip (Leveridge et al., 2002). More localised, steeply plunging folds near the Cawsand Fault also indicate at least one phase of sinistral movement (Leveridge et al., 2002). The approximately 15° to 20° rotation of strike between the Portwrinkle–Rame and Portnadler faults indicates sinistral shearing between them, but, in the area between the Portwrinkle–Rame and Hoodney Cove faults (not on map due to the scale of the fault), a 45° clockwise rotation of strike implies a substantial dextral displacement subsequent to the sinistral movement (Leveridge et al., 2002). Varying cumulative vertical movement components are evident along the faults, with downthrows to north-east or south-west. There is an estimated 200 m downthrow to the south-west on the Rame Fault between Crafthole and Tregantle Fort (Leveridge et al., 2002).

Dextral displacement of the margin of the Bodmin granite metamorphic aureole by 750 m along the Portwrinkle–Rame Fault at Kilham indicates movement after early Permian times, as does the brecciation on the Kingsand Rhyolitic Formation along the Cawsand Fault at Kingsand, but no evidence has been revealed that might further constrain particular movements (Leveridge et al., 2002).

5.4 FOLDING

Folding in the South-west England region is predominantly associated with Carboniferous and older rocks. The Permian and younger rocks are generally unfolded except where adjacent to faults.

In north Devon (Figure 29) fold axes are subhorizontal with an easterly trend and are overturned to the north and face upwards in this direction (Sanderson and Dearrman, 1973). The amount of overturning varies throughout north Devon. At Ilfracombe, slaty cleavage dips about 45° to the south but at Morte Point it is subvertical (Sanderson and Dearman, 1973). From Barnstaple to the south of Bude folds are typically trending to the east and upright with subhorizontal axes (Figure 29; Sanderson and Dearman, 1973). In the northern and southern part of this area there is overturning of the folds (Sanderson and Dearman, 1973). Southwards the folds are trending to the east and overturned as at Okehampton (Figure 29; Sanderson and Dearman, 1973). This transitions still further south into recumbent folding near Widemouth (Figure 29; Sanderson and Dearman, 1973). The recumbent primary folds have an easterly trend with subhorizontal cleavage except where refolded by small scale folds associated with low angle normal faults (Sanderson and Dearman, 1973). These faults and their associated folds become very common towards a zone between Tintagel and Lydford (Sanderson and Dearman, 1973).

In a narrow 5–10 km-wide zone that runs between Tintagel and Lydford, there is intense deformation (Figure 29). This zone widens west of Lydford towards Tavistock and the deformation intensity decreases (Sanderson and Dearman, 1973). The intense deformation results in strong stretching within the slaty cleavage and rotation of the fold axes to form oblique folds with axial directions roughly north–south (Dearman 1969; Sanderson and Dearman, 1973). The occurrence of oblique folds is characteristic of this area (Sanderson and Dearman, 1973).

In the area southwards from the coast at Polzeath past Bodmin and to Dartmoor (Figure 29), folds return to south-facing recumbent folds with east-north-east-trending axes (Sanderson and Dearman, 1973). The folds are generally open to close, flattened flexural folds similar to the area north of the high strain zone (Sanderson and Dearman, 1973). The southern margin of this area is at a major facing confrontation with folds to the south being north-facing with east-north-east axes and recumbent (Figure 29). Just south of Newquay, folds become more inclined and overturned to the north. This continues southwards to Perran Bay (Sanderson and Dearman, 1973).

The area between Perranporth and Hayle (Figure 29) has primary folds, which are recumbent with east-north-east-trending axes and face to the north or north-west (Sanderson and Dearman, 1973). Throughout this zone, the primary folds are considerably affected by later mesoscopic upright folds with an intense crenulation cleavage (Sanderson and Dearman, 1973). The southerly steepening of axial planes south of Newquay resulted from refolding in a large scale monoclinal complex, which is overturned to the south (Sanderson and Dearman, 1973).

In southern Cornwall (Figure 29), the primary folds’ axial planes dip gently or moderately to the south-east or south-south-east (Sanderson and Dearman, 1973). The inclined nature of the axial planes of the folds is probably a late-phase feature associated with more intense folding in the south (Sanderson and Dearman, 1973).

5.5 UNCERTAINTY

Much of the bedrock geology of the South-west England region is overlain by superficial deposits, which conceal much of the structure of the region. This hinders the mapping and understanding of the structure of the region and increases the uncertainty of the geometry and position of such faults and folds. Faults are generally well constrained in coastal sections but poorly understood inland. A fault is recognised as being present because distinctive units of strata are offset by varying amounts relative to one another, both horizontally and vertically, 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.

The presence, subsurface location and attitude of faults may be supported 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 exploration, provide greater resolution and thus permit more accurate identification, location and mapping of fault(s) and other structures in the subsurface. Seismic data is limited in the South-west England region to an area east of Sidmouth, Ottery St Mary and Honiton and south of Crewkerne. Offshore there is limited seismic data.

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 South-west England 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 SOUTH-WEST ENGLAND

There is some information related to groundwater in the depth range of interest, i.e. between 200 to 1000 m depth in the South-west England region. However, the majority of the information is related to the relatively shallow groundwater system which 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 regional groundwater flow systems in the South-west England region are conceptualised as being controlled by the broad distribution of geological units and the regional geological structure; the hydrogeological characteristics of those units; topography and the distribution of recharge, and hydraulic boundary conditions, such as the coastline (the Bristol Channel and Celtic Sea to the north and the English

Channel to the south) and some of the rivers in hydraulic connection with active groundwater systems, such as the River Otter.

The GVS for the South-west England region (Table 3) divides rock units into two broad lithostratigraphical systems: Palaeozoic basement rocks and igneous intrusions, mainly comprised of deformed and metamorphosed Carboniferous and older sediments and intruded by the Cornubian granite batholith; and a younger Permian to Palaeogene sedimentary cover.

The South-west England region is underlain by basement rocks characterised by generally poor primary permeability. For example, in the Culm Supergroup, groundwater flow is typically through fractures and focused in the upper 50 to 60 m, with limited flow below this depth (Leveridge, 2008). The granite of the Cornubian batholith that is intruded into the basement rocks also has low matrix permeability, with fractures primarily controlling flow within it and also within the surrounding altered country rock (e.g. (Jones et al., 2000). Carboniferous and Devonian limestones are designated as principal aquifers, and may be locally important for groundwater supply, particularly on the south coast, where their permeability may have been enhanced through the development of karst. In the east of the region, the older basement rocks are overlain unconformably by sedimentary cover rocks that include the Chalk Group, Upper Greensand, Sherwood Sandstone Group and the Permian sandstones, all principal aquifers. However, the Chalk Group and Upper Greensand Formation are restricted to the top of hills and do not supply significant volumes of water in the region. The younger sedimentary cover rocks, which include the regionally significant principal aquifers, generally dip gently to the east and are continuous to depths of >1100 m in the east. East of the outcrop, the aquifers become confined by large thicknesses of the low-permeability Lias Group and Mercia Mudstone Group.

There is very little information on regional groundwater flow at depths of >200 m in the literature reviewed; the information that is available is primarily associated with the hydrogeology of mineralised and mined units in the vicinity of the granites. Shallow groundwater flow tends to follow the topography and discharge at the coast and in the river valleys (Barton et al., 2011). This groundwater generally has short residence time in the aquifers (Barton et al., 2011).

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

- one system in the sedimentary cover rocks of Permian to Palaeogene age
- one system within the relatively low-permeability basement rocks and igneous intrusions of Carboniferous age and older

Rocks from both these systems are found in the depth interval of interest across the region. There are a range of pathways (both known and potential) for groundwater movement between these systems, associated with both regional-scale structures and anthropogenic features (see Section 8). For example, mine dewatering and adit drainage associated with mineral mining in the vicinity of granitic intrusions throughout the region have impacted on groundwater levels and in some cases reversed hydraulic gradients and influenced deep and shallow groundwater flow (British Geological Survey, 1990). In the vicinity of the mineral mines in and around the granites, there can be enhanced flow from surface waters to depths of 2 km, as evidenced by the tritium in springs issuing at depths of 700 m into mine adits or more (Burgess et al., 1982).

6.3.1 Hydrogeology of the sedimentary cover rocks

6.3.1.1 Chalk Group and Upper Greensand Formation

The youngest bedrock aquifer is the Chalk Group, a fine-grained, fractured limestone**.** While this group forms the most important principal aquifer in the UK (Allen et al., 1997) it is only present locally in the region, with minor outcrops on or near the tops of hills or within faulted blocks (Scrivener et al., 2014). The Upper Greensand Formation underlies the Chalk Group and comprises fine-grained sandstone, and siltstone. Like the Chalk Group, the Upper Greensand Formation is only present in the far east of the region; neither are regionally important aquifers and neither are present in the depth interval of interest. The Chalk Group can be in hydraulic contact with rocks of the Upper Greensand Formation (British Geological Survey, 2016). The Upper Greensand Formation is underlain by Mercia Mudstone Group or Lias Group rocks, and typically discharges as springs along the flanks of the outcrop (Scrivener et al., 2014). The Upper Greensand Formation and Permian breccias are in hydraulic continuity in a small area north of Torquay (Selwood et al., 1984). However, it overlies the Mercia Mudstone Group and Lias Group more commonly, with mudstones of the Great Oolite Group in between in a small area in the far east of the region.

6.3.1.2 Inferior Oolite Group

The Inferior Oolite Group is present just in the eastern part of the region. The group comprises limestone, sandstone, siltstone and mudstone, and crops out in two small areas within the region. These rocks do not occur in the depth interval of interest. The Inferior Oolite Group overlies rocks of the Lias Group. The formation is not of regional hydrogeological significance.

6.3.1.3 Lias Group

In this region the Lias Group generally comprises mudstones and silty mudstones with some interbedded limestone bands (Edwards, 1999; Scrivener et al., 2014). It is present in the eastern part of the region and north under the Bristol Channel and typically dips to the east with the other post-Carboniferous rocks in the region. Where present, the Lias Group crops out except where covered by Chalk Group, Upper Greensand Formation rocks and the Inferior and Great Oolite groups. This unit always overlies the Mercia Mudstone Group, resulting in a combined large thickness of predominantly mudstone, particularly to the east.

There is little information about the hydraulic properties of the Lias Group at depths of >200 m in the literature reviewed. The Lias Group is not known to be used for water supplies in the region (Edmonds et al., 1975) as its permeability is generally considered to be too low (Edwards, 1999). However, small quantities of water can be obtained from fractured interbedded limestones, such as the Blue Lias Formation (Whittaker and Green, 1983; Edwards, 1999) with high-yielding boreholes typically adjacent to the base of the overlying Upper Greensand Formation (Scrivener et al., 2014). Groundwater from the Lias Group is generally found to be hard (Edwards, 1999).

6.3.1.4 Mercia Mudstone Group

The Mercia Mudstone Group is a succession of red mudstones with local occurrences of sandstone, gypsum and halite (Allen et al., 1997). It is the dominant outcropping rock type in the east of the region. East of the outcrop, it dips to the east under rocks of the Lias Group.

There is no information about the hydrogeology of the Mercia Mudstone Group at depths >200 m in the literature reviewed. Locally the Mercia Mudstone Group is considered to have very low permeability compared to other rocks in region (Edmonds and Williams, 1985) with water supplies not obtainable from most of the unit (Edmonds et al., 1975). Higher groundwater yields arise from interbedded sandstones (‘skerries’) within the mudstones (Edmonds and Williams, 1985; Jones et al., 2000), and fractures (Whittaker and Green, 1983; Edwards, 1999), which can be enhanced by solution (Hobbs et al., 2002). The Environment Agency (2016) notes that private boreholes exploit the lower sandstone horizons in the Sidmouth Mudstone Formation east of Ottery St Mary.

Higher yields occur in proximity to the Upper Greensand Formation, indicating that this water has drained from the directly overlying Upper Greensand Formation (Scrivener et al., 2014). The presence of skerries results in multilayered confined aquifers that can give rise to artesian boreholes (Scrivener et al., 2014). In the Taunton area, the basal beds are in hydraulic continuity with permeable beds of the Sherwood Sandstone Group.

In the Mercia Mudstone Group, the groundwater quality is typically hard. It also has a high (>1000 mg/l) total dissolved solids (TDS), noticeably higher than in underlying Sherwood Sandstone Group groundwater (Walton, 1982). The chemical composition is due to calcite and gypsum dissolution (Walton, 1982; Edwards, 1999). Brine was obtained from the Puriton Borehole (Figure 3) on the north-east border of the region; this borehole encountered rock-salt (halite) in the Mercia Mudstone Group at depths between 183 and 219 m (Edmonds and Williams, 1985).

6.3.1.5 Sherwood Sandstone Group

The Sherwood Sandstone Group comprises sandstone, pebble layers, siltstone and mudstone (British Geological Survey, 2016). This unit is a principal aquifer and the main aquifer of west Somerset and east Devon (Allen et al., 1997). It is often considered as a single aquifer with the underlying Permian sandstones, but the Aylesbeare Mudstone Group may act as a confining layer separating the two aquifers (Allen et al., 1997). The Sherwood Sandstone Group is present at the surface in a relatively narrow outcrop to the east of Exmouth and north towards Minehead. The group dips to the east (Allen et al., 1997), becoming confined by the Mercia Mudstone Group (Waters et al., 2015).

The Chester and Helsby Sandstone formations are the main aquifer units in the Sherwood Sandstone Group in the South-west England region. The Helsby Sandstone Formation is a fine to medium-grained sandstone with occasional cemented bands (Institute of Geological Sciences, 1982). The Chester Formation comprises sandy conglomerates with pebbles, cobble and boulder-sized clasts with beds of sandstone throughout (Allen et al., 1997). These formations are separated by an unconformity (Allen et al., 1997) in the east, and vertical groundwater movement between aquifers is reduced by a less-permeable iron pan (Allen et al., 1997). To the west of the Otter Valley and north of Uffculme (Walton, 1982) they are generally in hydraulic connection (Edwards and Scrivener, 1999). The confined Chester Formation may be locally artesian, reflecting topographically higher recharge areas (Institute of Geological Sciences, 1982).

There is little information about the aquifer at depths >200 m but there is information for the aquifer at shallower depths. Groundwater flow in the Sherwood Sandstone Group is primarily intergranular, but with some fracture flow increasing the bulk permeability (Allen et al., 1997; Edwards and Scrivener, 1999).

Most chemical information comes from the unconfined part of the aquifer at outcrop (Bearcock and Smedley, 2012). Overall, shallow water in the Sherwood Sandstone Group is dominantly influenced by carbonates in the aquifer matrix (Bearcock and Smedley, 2012), and is of $CaHCO_3$ type. Five sampled waters from deep or artesian boreholes in the Chester Formation have very low tritium concentrations, indicating the presence of older groundwater under confined or semi-confined conditions, with relatively immobile waters several kilometres from outcrop (Walton, 1982). Fresh groundwater is restricted to unconfined conditions up to 5 km downdip in the Sherwood Sandstone Group aquifer due to increases in TDS with residence time (Allen et al., 1997).

6.3.1.6 AYLESBEARE MUDSTONE GROUP

The Aylesbeare Mudstone Group consists of reddish-brown mudstones with some sandstone and siltstone (Allen et al., 1997). It is overlain by the Sherwood Sandstone Group and overlies Permian-aged sandstones. It acts as a confining layer to the underlying Permian sandstone and separates it from the Sherwood Sandstone Group above (Allen et al., 1997; Institute of Geological Sciences, 1982).

Little is known about the hydraulic properties of the Aylesbeare Mudstone Group at depths >200 m bgl. The Aylesbeare Mudstone Group is generally regarded as an aquiclude but small supplies are possible from interbedded sandstone horizons (Edwards and Scrivener, 1999) such as the Vexford Breccias (Edmonds and Williams, 1985) and the Exmouth Mudstone and Sandstone Formation. This latter formation is locally considered an aquifer (Allen et al., 1997). Most groundwater flow is thought to be through fractures, which are likely to be more transmissive through sandstones than mudstones (Jones et al., 2004).

The quality of groundwater in the Permian mudstones is variable; Na and Cl concentrations may be high, due to the presence of evaporites in the rocks (Institute of Geological Sciences, 1982; Edwards and Scrivener, 1999).

6.3.1.7 PERMIAN-AGED SANDSTONES

The Dawlish Sandstone Formation of the Exeter Group in the Permian sandstone unit is considered a principal aquifer in the east of the region. In the South-west England region, the Permian sandstone comprises interbedded sandstone and conglomerate with subordinate mudstones and marls. Lithology is highly variable laterally and vertically (Institute of Geological Sciences, 1982). Underlying Palaeozoic rocks form the hydraulic base of the aquifer (Allen et al., 1997). Artesian conditions may exist within the Dawlish Sandstone Formation due to semi-confining mudstone layers within the unit (Environment Agency, 2016). Groundwater quality in Permian rocks along the east of the south coast of the region has a moderate hardness.

In north-west Somerset the Wiveliscombe Sandstones have low matrix permeability (Edmonds and Williams, 1985) and are well cemented. Permian aged sandstones in the Crediton trough are also well cemented and groundwater flow is through often poorly developed fractures (Institute of Geological

Sciences, 1982). Groundwater in Permian rocks of the Crediton trough is harder than surrounding Carboniferous strata.

Little is known about the hydraulic properties of the aquifer at depths >200 m. Some formations are water bearing and developed for public water supply (Edmonds et al., 1975). Their aquifer properties depend on the local lithology intersected by boreholes and the presence of fractures; interleaved sandstones, breccias and mudstones result in variable aquifer properties such that it can be difficult to extrapolate this information (Allen et al., 1997).

6.3.2 Hydrogeology of the basement rocks

6.3.2.1 PERMIAN INTRUSIONS: CORNUBIAN GRANITE

The Cornubian granite comprises biotite granite, with less common tourmaline granite and topaz granite (Smedley and Allen, 2004). The granite underwent widespread mineralisation with hydrothermal activity after emplacement. It generally has a low intergranular permeability (Burgess et al., 1982), but can be highly fractured, allowing groundwater flow (British Geological Survey, 1990; Edwards and Scrivener, 1999). Fractures are particularly prevalent in weathered zones, generally 10–20 m from the surface (British Geological Survey, 2016; Selwood et al., 1984; Leveridge et al., 1990), and are thought to be tighter >30 m (British Geological Survey, 1990). However, similar radon contents at depth and significant inflows of saline waters into deep mines indicate that the extent of fracturing might be similar at about 700 m to the surface (Burgess et al., 1982).

Shallow groundwater (mostly <30 m bgl) in the granite is characteristically acidic (Edmonds et al., 1968; Selwood et al., 1998; Edwards and Scrivener, 1999). It is also soft (British Geological Survey, 1990; Leveridge et al., 1990), and electrical conductivity measurements from five boreholes up to 240 m in the Carnmenellis granite indicate no noticeable variations, and therefore no discernible stratification with depth (Smedley and Allen, 2004).

However, there is also evidence of groundwater circulation in the depth interval of interest. At depths of 300 m or more, saline groundwater with high total dissolved solids (TDS) and temperatures up to 55ºC were discharged into active tin mines through springs issuing from fractures and lodes in and around the Carnmenellis granite (British Geological Survey, 1990; Smedley and Allen, 2004). A saline spring in the South Crofty Mine at 820 m has been present for over 100 years. Assuming a constant flow rate of 3.5 l/s over the last 100 years, the granite catchment of this spring is estimated to have a storage of at least 6.6 x 10^6 m^3 (Burgess et al., 1982), only one per cent of the total saline water likely to be stored in the granite (Downing and Gray, 1986). When active, up to 7.6 x 10^4 m^3/day of saline water was pumped from the South Crofty, Pendarves, Wheal Jane and Mount Wellington mines (Burgess et al., 1982). However, mine water TDS can also vary significantly over a small vertical distance, with more than two orders of magnitude difference reported between 611 and 693 m in the South Crofty Mine (Burley et al., 1984). Studies of the composition of brines in the granite (Downing and Gray, 1986) suggest a meteoric origin, while Na/K geothermometers indicate an equilibrium temperature of 54 $^{\circ}$C for the water, indicating a depth of origin of 1.1 to 1.2 km, some 440 m below the depth of discharge into the South Crofty Mine (Burgess et al., 1982). Enhanced ^{4}He values and U series geochemistry indicate components of the brine with ages of 10 000 to 1 000 000 years (Burgess et al., 1982; Smedley and Allen, 2004). However, the presence of tritium and δ^{14}C isotopes suggest 40 per cent of the saline water is more recent (1953–1978) and there has therefore been some mixing (Burgess et al., 1982). This indicates percolation of modern recharge to at least 700 m bgl where it has mixed with older, deeper, saline waters (Burgess et al., 1982; Downing and Gray, 1986; Smedley and Allen, 2004). This rapid percolation of recent groundwater might be possible to 1.2 km depth, with vertical drainage accelerated by mining (Downing and Gray, 1986). This might also explain locally distorted isotherms (British Geological Survey, 1990).

The granite intrusions have also influenced properties of surrounding rocks (Carboniferous and Devonian rocks), creating thermal aureoles 1 to 7 km in width (Smedley and Allen, 2004). While the aureole consists of multiple formations, it constitutes a single hydrogeological unit due to alteration by the granite intrusion (British Geological Survey, 1990). The unit has a low primary permeability. However, a 256 m-deep borehole in Penryn yielded groundwater derived from major fracture zones, and artesian conditions can be encountered (British Geological Survey, 1990).

6.3.2.2 Carboniferous Limestone Supergroup

Tournaisian to Visean strata belonging to the Carboniferous Limestone Supergroup, a principal aquifer, are predominantly composed of mudstones with thin, discontinuous limestones (Allen et al., 1997). They are present only in a small area onlapping onto the Quantock Hills in the north-east, dipping steeply to the north and south. Their highly complex structural history has resulted in folding and faulting of the unit, which has fragmented the outcrop (Allen et al., 1997).

Little is known about the hydrogeological properties of this unit in the South-west England region. It is only likely to constitute an aquifer of limited local importance due to the predominance of mudstones and low primary permeability (there are no known laboratory measurements (Jones et al., 2000)). Fractures can allow some groundwater flow at shallow depths, as evidenced by the discharge of springs from the limestone and occasional wells.

6.3.2.3 Teign Valley and Tintagel groups

The Teign Valley and Tintagel groups are part of the Culm Supergroup. The Teign Valley Group comprises predominantly pyritic mudstone, siliceous mudstones, bedded chert and some thin limestones. The Tintagel Group comprises slates with siltstones and carbonate nodules and limestone and tuffs with agglomerate and lavas.

There is little hydrogeological information on this group >200 m in the literature reviewed. Both mudstones and the occasional sandstones in the Carboniferous are fine-grained and of low permeability (British Geological Survey, 2016). Intergranular flow is generally negligible (Freshney et al., 1979; Selwood et al., 1984). However, rocks can yield water (Freshney et al., 1979; Selwood et al., 1984; Edwards and Scrivener, 1999) where faulted or fractured (particularly if thermally metamorphosed by adjacent granite). Groundwater supplies often diminish or dry up in the summer, suggesting that fracture systems are rarely interconnected (Edmonds et al., 1968; 1975; Freshney et al., 1979). Fracture aperture decreases with depth such that the highest yields are from only 50 m below the water table (Edwards and Scrivener, 1999).

Groundwater from the Carboniferous sedimentary rocks has low TDS (Edmonds et al., 1968) and a generally low total hardness (Freshney et al., 1979; Edmonds et al., 1968; McKeown et al., 1973).

6.3.2.4 Late Devonian rocks

Late Devonian mudstones are prevalent across the South-west England region and are described in Section 4.2.2. Devonian rocks vary lithologically relating to deposition in a series of variably interconnected basins comprising mudstone-dominated sequences in deeper water basinal settings to sandstone and limestone-dominated sequences towards the intervening highs. The sequences are extensively fractured and folded (Institute of Geological Sciences, 1982). They underlie the Culm Supergroup, and they also lie unconformably beneath the Permian rocks onlapping onto the Quantock Hills, dipping steeply to south.

There is no information about the hydrogeological characteristics of these rocks at depths of >200 m in the literature reviewed. At shallow depths, the hydrogeological properties of the rocks are variable, but they are generally not very porous or permeable because they are dense and well cemented (Edmonds et al., 1979). Groundwater flow predominantly occurs in faults and fissures (e.g. Edmonds et al., 1979; Leveridge et al., 1990; Barton et al., 2011; Jones, et al., 2000). The more open of these fractures provide channels for groundwater (Whittaker and Green, 1983) although these are often not thought to be interconnected due to common unsustainable borehole yields (Edmonds et al., 1979; Leveridge et al., 1990). Vertical permeability is much lower than horizontal permeability (Leveridge et al., 1990). Around the granite intrusions these rocks have undergone significant thermal metamorphism and behave as a single unit with other country rocks.

6.3.2.5 Mid Devonian rocks

Mid Devonian rocks consist of a highly varied sequence of mudstones, slaty mudstones, and sandstones, and include Mid and Late Devonian limestones, which are principal aquifers. There is no hydrogeological information about these units at depths of >200 m in the literature reviewed.

Mid Devonian rocks tend to be well cemented and have a low intergranular permeability but with some fracture flow (Selwood et al., 1998; Edmonds and Williams, 1985; Edmonds et al., 1985; Leveridge et al., 2008). In the north of the region, boreholes in the Lynton Formation and the Hangman Sandstone Formation provide limited groundwater resources (Selwood et al., 1998; Edwards, 1999). However, the main groundwater resources are obtained from the Devonian limestone principal aquifer.

The Devonian limestone principal aquifer is found along the south coast, between Teignmouth and Plymouth. Around Torquay and Newton Abbott, the Devonian limestone is commonly massive (Selwood et al., 1984) and has been recrystallised, resulting in very little primary permeability (Barton et al., 2011). It does, however, form well-fissured, karstic aquifers with extensive solution channels, dolines, solution pipes, hollows and underground cave systems, indicating that underground flow is often rapid (Selwood et al., 1984; Leveridge et al., 1982). Groundwater flow can, however, be slowed by infill by younger sediments (Barton et al., 2011). Cave systems observed at the coast appear better developed than those observed in quarries, possibly due to enhanced weathering. This might be due to preferential selection of good quality rocks for quarries (Barton et al., 2011). Water table elevations are often discontinuous (Barton et al., 2011). Due to the karstic nature of the aquifer, yields are highly variable with dry boreholes where no water-bearing fractures are encountered. Small quantities of water have been obtained from Devonian limestones (Edmonds et al., 1975). Springs can occur along faulted junctions with slaty mudstones (Barton et al., 2011) or fissures in the limestone.

Groundwater from the limestones is hard (Leveridge et al., 2002). A large part of the outcrop is probably in hydraulic continuity with the sea (Barton et al., 2011) and in the Plymouth area, brackish or salt water is often obtained from boreholes (to 900 mg/l Cl) (Leveridge et al., 2002).

6.3.2.6 Early Devonian rocks

Early Devonian rocks consist of sandstones, mudstones, slates and siltstones (Selwood et al., 1998). There is no hydrogeological information on this unit >200 m in the literature reviewed. Hydrogeological properties of Early Devonian mudstones <200 m are similar to Mid and Late Devonian mudstones; they are generally not very permeable because they are dense and well cemented (Edmonds et al., 1975). Groundwater flow predominantly occurs in faults and fractures (Edmonds et al., 1979; Leveridge et al., 1990; Barton et al., 2011; Jones et al., 2000).

6.3.2.7 Devonian igneous intrusions and hornblende schist

These rocks form part of the Lizard Complex (comprising the Lizard ophiolite and underlying Devonian hornblende schists and mica schists). They comprise metamorphosed and deformed mantle units (e.g. serpentinised peridotites), crustal units (including gabbros, dykes and amphibolites) with some subsidiary later syndeformational intrusions. There is no information on the hydrogeology of these units in the literature reviewed.

6.4 EVIDENCE FOR CONNECTIONS BETWEEN GROUNDWATER SYSTEMS

6.4.1 Separation

The Mercia Mudstone Group confines the Sherwood Sandstone Group in the east of the region (Allen et al., 1997). However, there are no regionally significant rock types or features that produce a hydrogeological separation between deep and shallow groundwater systems.

6.4.2 Geological pathways

6.4.2.1 Thermal springs

For the purposes of this report, thermal springs are defined as those with waters >15ºC. There is no evidence for thermal springs in the region. However, there is evidence for an elevated shallow groundwater temperature of 15.6°C in a 19 m bgl borehole in granite at Halabezack Farm to the north-west of Falmouth. In this borehole, the rest water level was at 3 m bgl although it is not clear at which depth the borehole was sampled or from which lithology (Leveridge et al., 2002).

6.4.2.2 FAULTS

Geological structure is an important control on groundwater flows and pathways in the South-west England region (Barton et al., 2011). Many faults control the location of springs, such as in the north-east (Wootton Courtenay) at a junction between the Hangman Sandstone Formation and Mercia Mudstone Group (Edwards, 1999). Faults in the Crediton Breccia Formation (Permian sandstone) often give rise to spring lines (Allen et al., 1997). Springs also probably issue from fractures near Grampound (Leveridge, 2008). Faults in this area increase groundwater flow at Ash Priors where two differing lithologies in the Sherwood Sandstone Group are juxtaposed, but elsewhere fault planes are strongly cemented and act as baffles (Institute of Geological Sciences, 1982). In the Helsby Sandstone Formation of the Sherwood Sandstone Group in the north-east coastal region, faults are said to impede groundwater flow due to cementation (Edwards, 1999) resulting in compartmentalisation of the aquifer (Allen et al., 1997). Compartmentalisation occurs in the Tone catchment (Allen et al., 1997). A small, faulted block of the Helsby Sandstone Formation in the valley of the River Sid was utilised for a water supply, but is not in continuity with the Otter Valley outcrop (Environment Agency, 2004). Some faults in the Sherwood Sandstone Group can allow pressure release of the confined waters and upwards infiltration of high-Fe waters from the Chester Formation to the Helsby Sandstone Formation (Walton, 1982).

6.4.2.3 KARST

There are many caves in Devonian limestones in Devon. On the south coast, Berry Head has many small caves formed at the marine/freshwater interfaces during high interglacial sea levels during the Pleistocene (Waltham et al., 1997). Kent’s Cavern, Torquay, contains 400 m of large, phreatic passages filled with thick clastic sequences truncated by the Ilsham Valley (Waltham et al., 1997). The largest caves in Devon are in Mid Devonian limestone in the valley of the River Dart and south-east of Dartmoor (Waltham et al., 1997). In north Devon, the outcrops are smaller but there are still small cave systems, including Napps Cave at Combe Martin (Waltham et al., 1997).

6.4.3 Anthropogenic pathways

There are a number of small clusters of deep (greater than 200 m below NGS datum) boreholes in the region (Section 8.10, Figure 36). Most of these have been drilled during the course of exploration for and the evaluation of mineral deposits, particularly those in Cornwall in the Callington, Bodmin, Camborne/Redruth and Hayle/Penzance/Helson areas. As many as 14 boreholes per 1 km^2 are recorded around Callington and 13 per km^2 around Camborne.

The south-west of the region has a long history of mining for minerals in veins resulting from ancient circulating fluids associated with the magma (British Geological Survey, 2016). Mines will likely locally increase the permeability (British Geological Survey, 1990) and public water supplies from groundwater may be abstracted from shafts and adits (British Geological Survey, 1990) and mines may be used for water storage (Leveridge et al., 1990). Mines around Newquay preferentially drain water (Flett et al., 1906) and, where adits are open, they allow conduit flow and act to lower the water table and influence shallow groundwater flow (British Geological Survey, 1990). The Wheal Jane and South Crofty mines dewatered areas down to 200 m over a lateral distance of 5 km (Smedley and Allen, 2004). This had a major impact on regional groundwater flow, creating artificial hydraulic gradients and inducing flow towards the mines (Smedley and Allen, 2004). However, shallow wells surrounding the Mount Wellington–Wheal Jane mine complex are not impacted by dewatering (Leveridge et al., 1990).

Post-mining water rebound can also impact local groundwater quality (Smedley and Allen, 2004) and some waters in adits are highly contaminated with the products of mine drainage (British Geological Survey, 1990).

Groundwater flow through mine systems interacts with regional structures. Water inflows to the South Crofty Mine group through a north-north-west-striking fault zone and pumping rates differed between levels (British Geological Survey, 1990).

There have been a number of geothermal experiments in the Carnmenellis granite (Dangerfield et al., 1998). A pilot study at the Rosemanowes Quarry site drilled boreholes to 2.5 km with inclined sections to intersect as many fractures as possible; these were then stimulated by hydraulic fracturing (Smedley and Allen, 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 South-west England 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 South-west England 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 buildup 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 30; RWM 2016b; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next one million years is open to conjecture (Loutre and Berger, 2000). This is because the impacts of global warming and the current melting of the Greenland Ice Sheet on the long-term climate system are poorly understood, although the general scientific consensus is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions means that their occurrence cannot be discounted.

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

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

7.2.2 A regional perspective

It is widely accepted that the South-west England region is situated just beyond the limits of continental and lowland-scale glaciation during the last two and half million years (Quaternary Period; Figure 30) (Clark et al., 2004; RWM, 2016a). Based upon the absence of evidence for past glaciations of this scale in the recent geological past, it is unlikely that the region will experience this scale of glaciation over the next million years except under exceptional circumstances (RWM, 2016b). However, the region may be affected by isostatic rebound and/or a glacier forebulge relating to the glaciation of an adjacent onshore (e.g. Wales) and/or offshore region (e.g. Bristol Channel or Irish Sea; RWM, 2016b). This may result in increased fracturing and fault reactivation within the subsurface, leading to earthquakes.

The extensive coastline of the South-west England region makes coastal areas of the region susceptible to saline groundwater incursion due either to global sea-level change (driven by global patterns of glaciation) or regional isostasy (RWM, 2016b). Saline groundwater incursion may alter the temporal and spatial patterns of groundwater behaviour.

The occurrence of highland glaciation within upland parts of South-west England region is currently a matter of considerable controversy within the geological community (Evans et al., 2012; Straw, 2013). Although few scientists doubt the theoretical possibility of small glaciers occurring in highland parts of South-west England, the geological evidence for glaciation is subtle and ambiguous, being open to alternative glacial and non-glacial interpretations (Evans et al., 2012; Straw, 2013). A worst-case scenario, and the one employed here, is that highland areas of the South-west England region may undergo multiple highland glaciations over the next million years, although these are likely to be of limited spatial extent (RWM, 2016b). Under such a scenario, glacial over-deepening over multiple glaciations may produce localised erosion, possibly extending to the very top of the depth range of interest (RWM, 2016b).

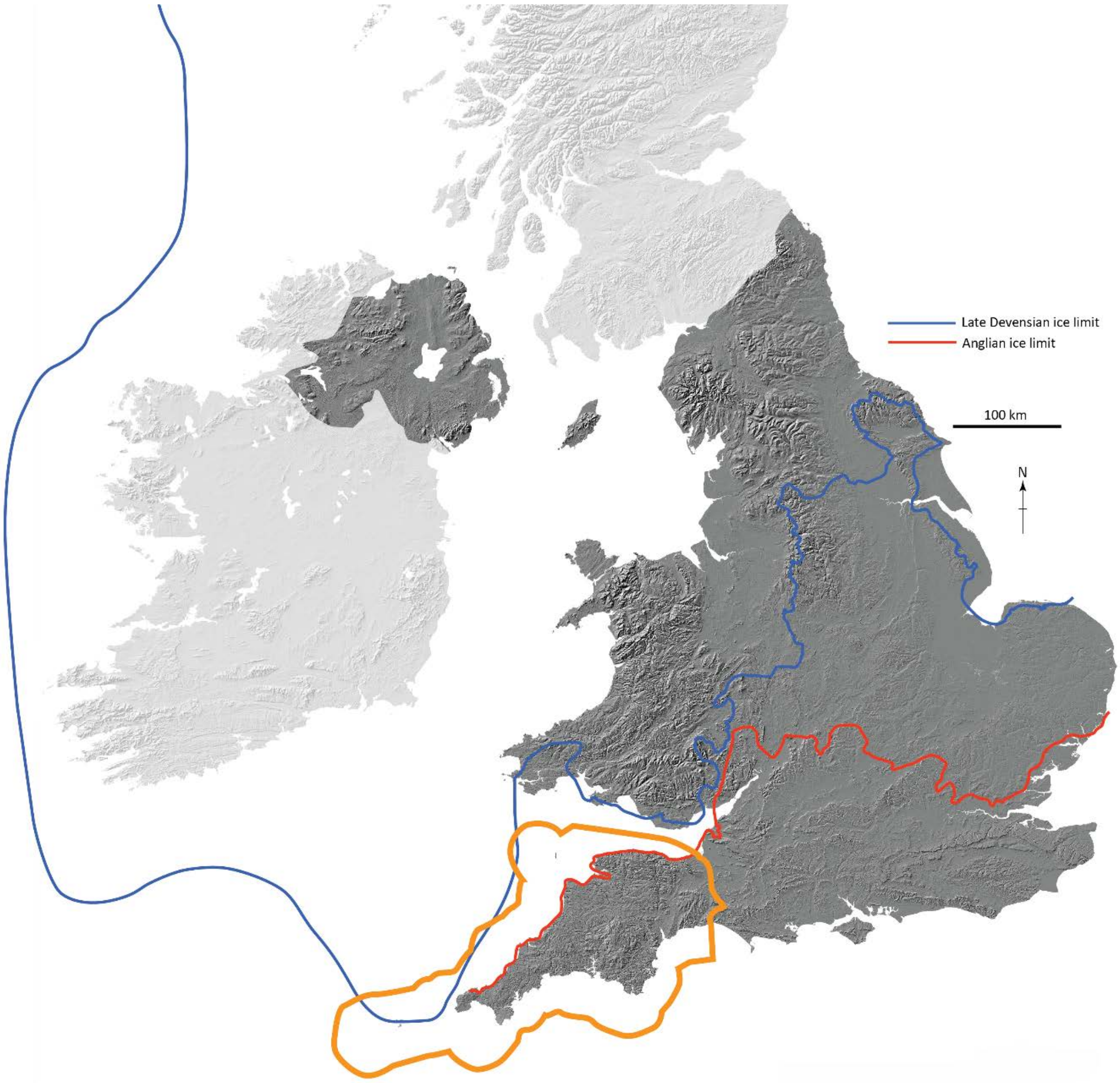

Figure 30 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and late Devensian (around 30 to16 ka). The location of the South-west England region is delineated by the orange line. Produced using Copernicus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

7.3 PERMAFROST

7.3.1 A UK-scale context

Permafrost (frozen ground) occurs when the temperature of the ground remains below 0°C for at least two consecutive years (French, 2007). Permafrost, therefore, develops where average air temperatures are much colder than the present day and consequently there is potential for significant thicknesses of permafrost to develop over decadal to centennial timescales (Busby et al., 2014). It is also important to note that permafrost and glaciation are not synonymous. Whilst many glaciated areas are subjected to periglacial processes, not all areas affected by permafrost will become glaciated. For example, areas situated to the south of the major limits of glaciation in the UK (Figure 30), 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 South-west England region will be subjected to the development of permafrost to a depth of a few hundred metres (Busby et al., 2014)). The development of permafrost can affect groundwater chemistry and behaviour and, in combination with possible localised glacial erosion in highland areas, future development of permafrost may be to several hundred metres beneath the current ground surface (RWM, 2016b).

7.4 SEISMICITY

7.4.1 A UK-scale context

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

Earthquake activity is greatest at the boundaries between the Earth’s tectonic plates, where the differential movement of the plates results in repeated accumulation and release of strain (Figure 31). 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 31).

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

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

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

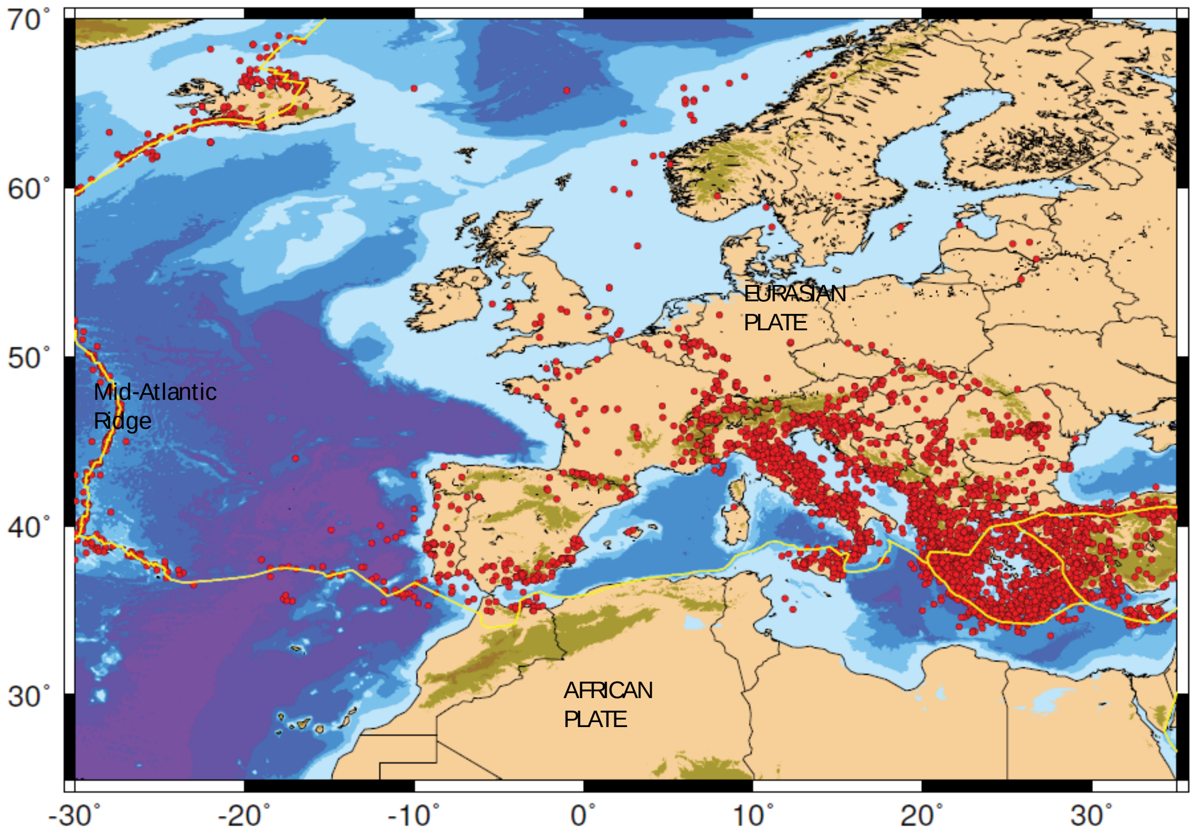

Figure 31 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

7.4.1.1 Seismicity catalogue

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

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

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

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

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

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

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

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

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

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

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

Figure 32 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 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 32).

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 32) 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 around20 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).

7.4.1.2 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 33 shows the distribution of focal depths in the catalogue. These are distributed throughout the crust and the maximum depth in the catalogue is 28 km. This suggests that there is a relatively broad seismogenic zone, i.e. the range of depths in the lithosphere where earthquakes are generated. The larger earthquakes, e.g. the 7 June 1931 Mw 5.9 Dogger Bank earthquake and the 19 July 1984 Mw 5.1 Lleyn earthquake, tend to occur at greater depths (Figure 33).

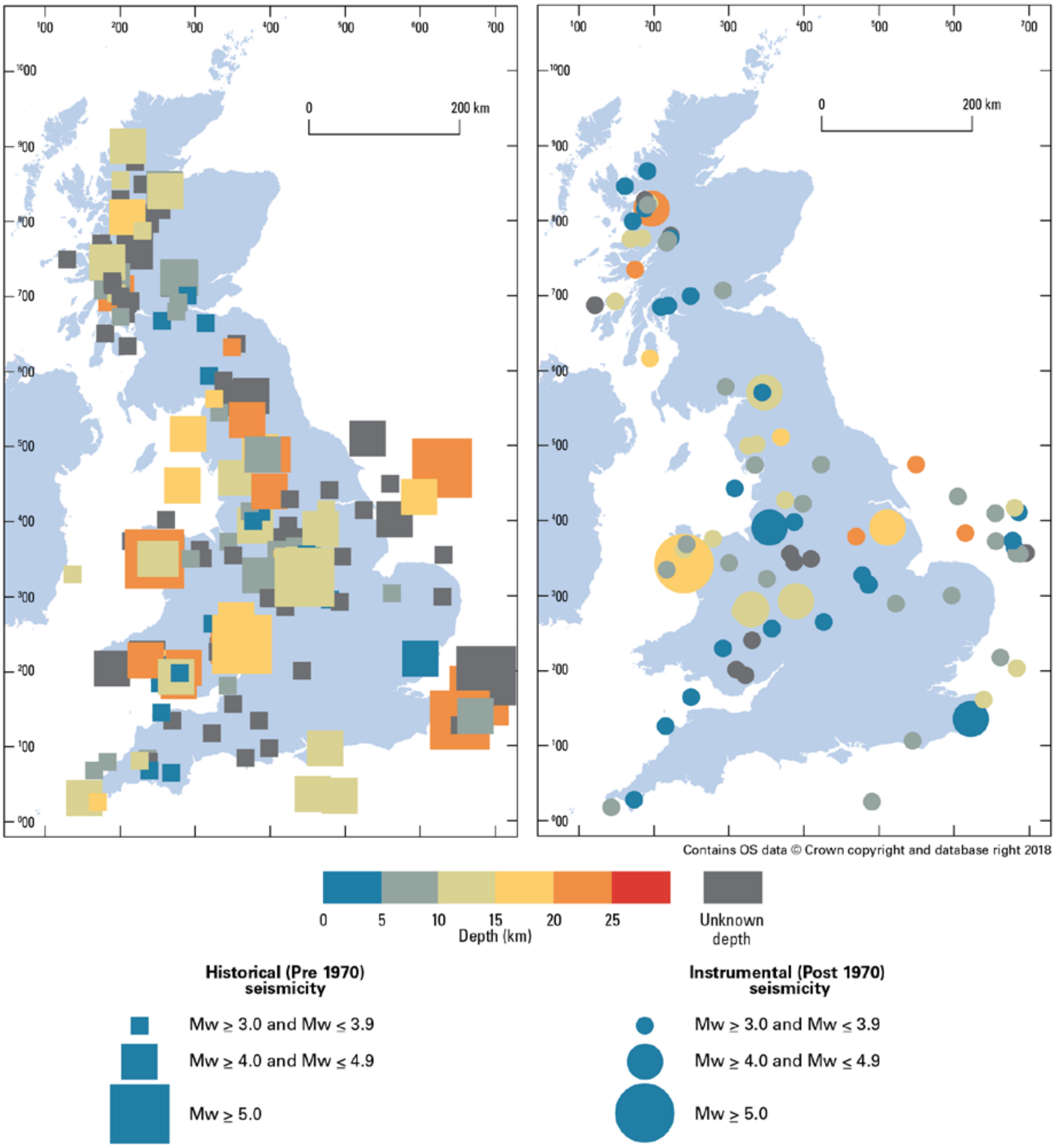

Figure 32 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

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

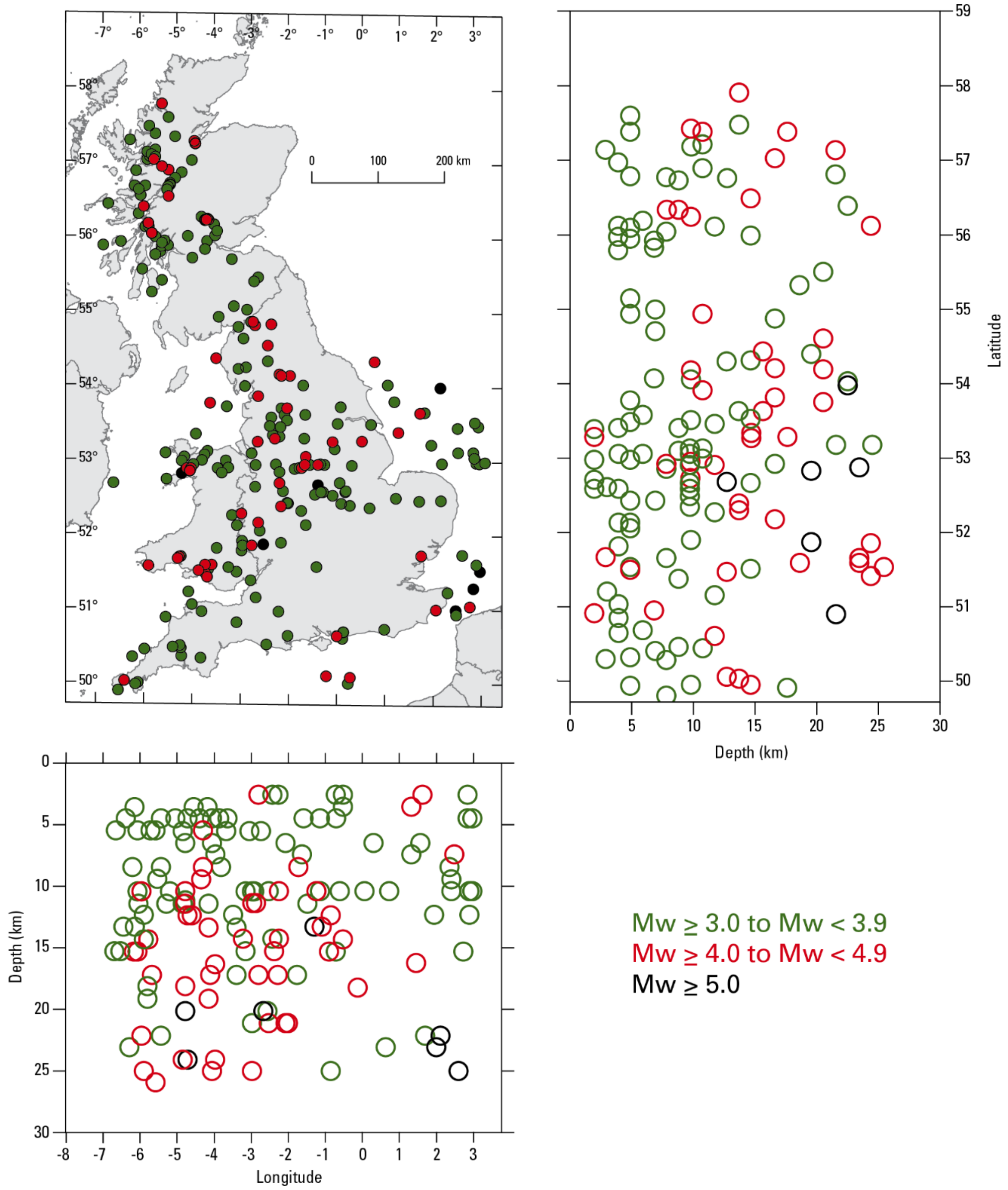

Figure 33 Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

7.4.1.3 Maximum magnitude

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

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

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

7.4.1.4 EARTHQUAKE ACTIVITY RATES

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

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

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

We have used the method of Johnston et al. (1994) to calculate the a and b values for the UK catalogue described 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.

7.4.1.5 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).

7.4.1.6 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.

7.4.2 A regional perspective

The South-west England region is characterised by relatively low levels of seismicity and small earthquakes (Mw <4) have occurred throughout the region (Figure 34). The spatial distribution of seismicity suggests that Cornwall is slightly more active than Devon, though a number of earthquakes have occurred in north Devon. The largest earthquake in the region had a magnitude of 4.1 Mw and occurred in western Cornwall in 1757. Musson (1989) assigns an epicentre for this earthquake just east of Penzance. This earthquake was felt throughout Cornwall and the Isles of Scilly and in the western part of Devon. More recently, a magnitude 3.5 Mw earthquake was recorded near Penzance in 1996.

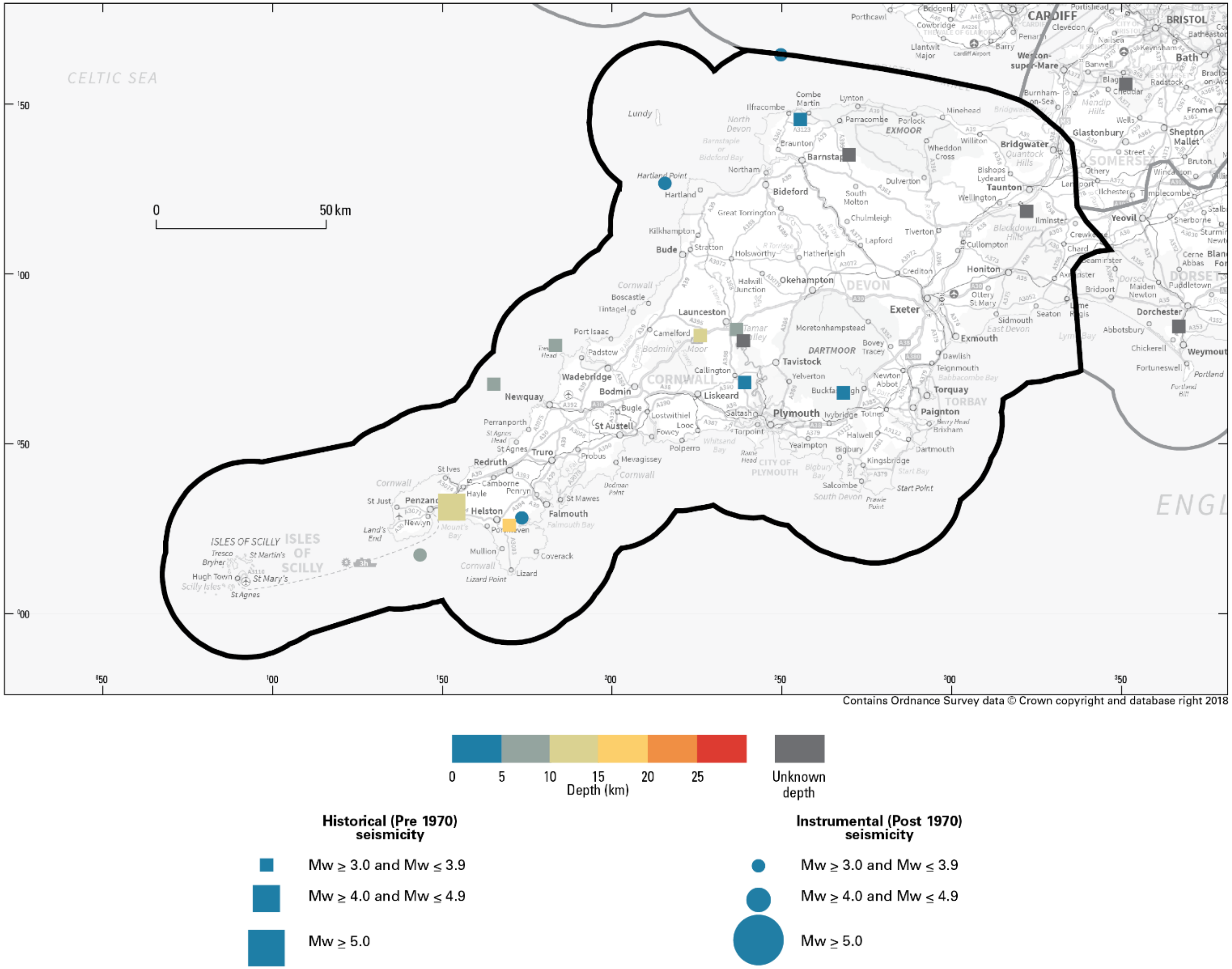

Figure 34 Historical and instrumentally recorded earthquakes in the South-west England region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

This section explains what is known of mineral resources in the South-west England 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

The South-west England region is well known for past copper and tin mining. A number of other commodities including iron ores, ‘Bideford Black’ (a poor-quality coal used as a pigment) and lignite have also been mined in the past. A small area in the east of the region, between Crewkerne and Bridport, is prospective for shale gas/oil. Parts of the large granite body that underlies much of the region have properties that give rise to some of the UK's highest geological heat-flow values, with resultant potential for exploitation of geothermal energy. Figure 35 shows the distribution of mineral resources in the region.

8.3 COAL AND RELATED COMMODITIES

Poor quality coal has been mined from the late Carboniferous south-east of Bideford for the pigment known as Bideford Black. None of the workings exceed a depth of 100 m below NGS datum. Lignite (brown coal) has been mined at several locations in Devon at depths less than 100 m below NGS datum.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

No evaporite minerals have been exploited in the region. The western edge of the Somerset salt field extends into north Devon (equivalent to the Triassic Dorset Halite Member). Halite is encountered between around 180–740 m deep below NGS datum and halite beds occur through up to 107 m of strata. There are considerable thicknesses of halite present in the Bristol Channel and the English Channel. Although these halite units are extensive, their extraction is unlikely to be economically viable in the foreseeable future. Feasibility of mining these resources depends on factors such as the commodity prices, geology, available technology, depth of deposits and distance to shore.

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. Slate, building stone and ball clay have been worked in the region by underground methods but at depths significantly less than 100 m below NGS datum.

8.6 VEIN-TYPE AND RELATED ORE DEPOSITS

Areas which 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.

The South-west England region has been extensively mined for metalliferous ores over at least 3000 years. From the 16th century some mines exceeded depths of 100 m below NGS datum. Mineralisation, and hence past mining, is concentrated into discrete areas, most of which are spatially related to the granite intrusions in the area. The orefield areas in the region are identified on Figure 35, these being the main Devon and Cornwall copper, tin, tungsten and lead orefield, and the west Cornwall copper, tin and tungsten orefield respectively. These two areas host most of the known mineralisation in the region. Large parts of the orefields are not intensively mineralised and have not been extensively mined or mined to depths exceeding 100 m below NGS datum. Due to the widespread distribution of mineral veins and the extent of past shallow mine workings it is not possible to discount the likelihood that these areas may become of interest to mineral exploration companies 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. All of the mineral veins known or suspected to have been mined to depths in excess of 100 m below NGS datum are plotted on Figure 35.

Mines in the Camborne area have been worked to depths exceeding 1 km, and several mines in other areas have been exploited to depths well over 500 m below NGS datum, some of the largest being Geevor, Redmoor, South Crofty and Levant. Iron ores have been mined in north-east Devon and west Somerset to depths of up to about 200 m below NGS datum.

Working mines

There is currently only one mine in the region that is working. This is Drakelands Mine, north-east of Plymouth, which is a tungsten and tin mine that commenced full operation in 2015 and is currently the third or fourth largest tungsten mine in the world. Current operations are based on an open pit mine, which is expected to reach a depth of 200 m once surface mining has been completed.

Potential future mines

There are a number of known ore deposits that are currently or have recently been evaluated for their metalliferous minerals. All have been mined to greater or lesser extent in the past. These are shown on Figure 35. All could be considered for exploitation in the future to depths that may exceed 100 m below NGS datum.

South Crofty Mine, near Camborne, is a copper and tin mine with a long history of mining with working extending to depths of over 1000 m below NGS datum. Deep mining ended in 1998, however, interest in a number of commodities present in the mine has continued since closure. A programme of borehole drilling, shallow trial mining and assessment has continued intermittently since soon after closure but is currently (April 2016) inactive.

The Treliver prospect is a tin ore body currently under evaluation near Indian Queens.

The Redmoor prospect is a tin and tungsten deposit north of Callington that has recently been drilled and is currently being evaluated for the potential development of a mine to depths of 600 m or more below NGS datum.

Both the Wheal Jane and Geevor prospects are associated with deep mines, worked to depths of more than 500 m and about 650 m below NGS datum respectively. Both mines were abandoned in the early 1990s when the price of tin was low. Each mine has resources remaining at depth and in nearby vein structures that may be of interest in future.

At Drakelands Mine the ore body extends deeper than that which will be mined in the open pit. Consideration is being given to extending the life of the mine by switching to underground extraction to depths likely to significantly exceed 100 m below NGS datum.

Potential for extracting ore deposits within other old mines in the region may be re-evaluated if metal prices warrant this in future. It is, however, unlikely that shallow and more isolated mines in the region will contain ore deposits of economic interest for the foreseeable future.

8.7 HYDROCARBONS (OIL AND GAS)

There are no conventional hydrocarbon fields on- or offshore in the region.

A small area in the eastern margin of the region around Crewkerne contains mudstones that have been identified as having some potential for shale gas and oil resource. This is the western margin of a large area of such rocks outside the region.

8.8 UNDERGROUND GAS STORAGE

There are no planned, under construction or operating underground gas storage facilities in the region. There seems to be little immediate prospect for gas storage in the region, including the offshore area being considered. Any potential probably lies in lined or unlined caverns in hard rock locations.

8.9 GEOTHERMAL ENERGY

The South-west England region is underlain by the Cornubian batholith, which is exposed at six main locations across the region, from Dartmoor to the Isles of Scilly. The granite body is radiothermal, which means the decay of natural radioactive elements generates heat within the rock. Consequently, parts of the South-west England region show some of the highest geological heat flow in the United Kingdom.

Heat-flow rates in the region are locally in excess of 120 mW/m^2 coinciding with geothermal gradients of 35–40 ^oC per kilometre. This would mean temperatures of 100^oC would be encountered at depth of about 2.5 km below the surface, and 180–200^oC at 4.5 to 5 km depth.

The region was evaluated for its geothermal energy potential in the late 1970s and early 1980s, testing the granites for their hot dry rock potential. Three boreholes were drilled at Rosemanowes Quarry, Penryn, in the Carnmenellis granite by the Camborne School of Mines, to a total depth of 2.6 km and the bottom-hole temperatures reached around 100 ^oC. A reservoir was created by hydraulic stimulation of the granite followed by a series of circulation tests.

There is no evidence for the granite in the South-west England region having transmissivity that would be sufficient for geothermal exploitation without stimulation of the geothermal reservoir rock. However, this is largely because of a lack of subsurface investigation of more permeable fault, fracture and weathered zones within the granites.

Geothermal plants which successfully intercept permeable zones or artificially increase the permeability of the granite could supply heat to local communities as well as energy to the national grid. Recently there has been renewed interest in geothermal heating from deep geothermal sources in Cornwall, with the Eden Deep Geothermal Plant having permission granted in 2010 to build the UK's first geothermal power plant with a capacity of up to 4MW at Bodelva near St Austell. Since approval, the project has stalled whilst funding is secured.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are a number of small clusters of deep (greater than 200 m below NGS datum) boreholes in the region (Figure 36). Most of these have been drilled during the course of exploration for and the evaluation of mineral deposits, particularly those in Cornwall in the Callington, Bodmin, Camborne/Redruth and Hayle/Penzance/Helson areas. As many as 14 boreholes per 1 km^2 are recorded around Callington and 13 per km^2 around Camborne.

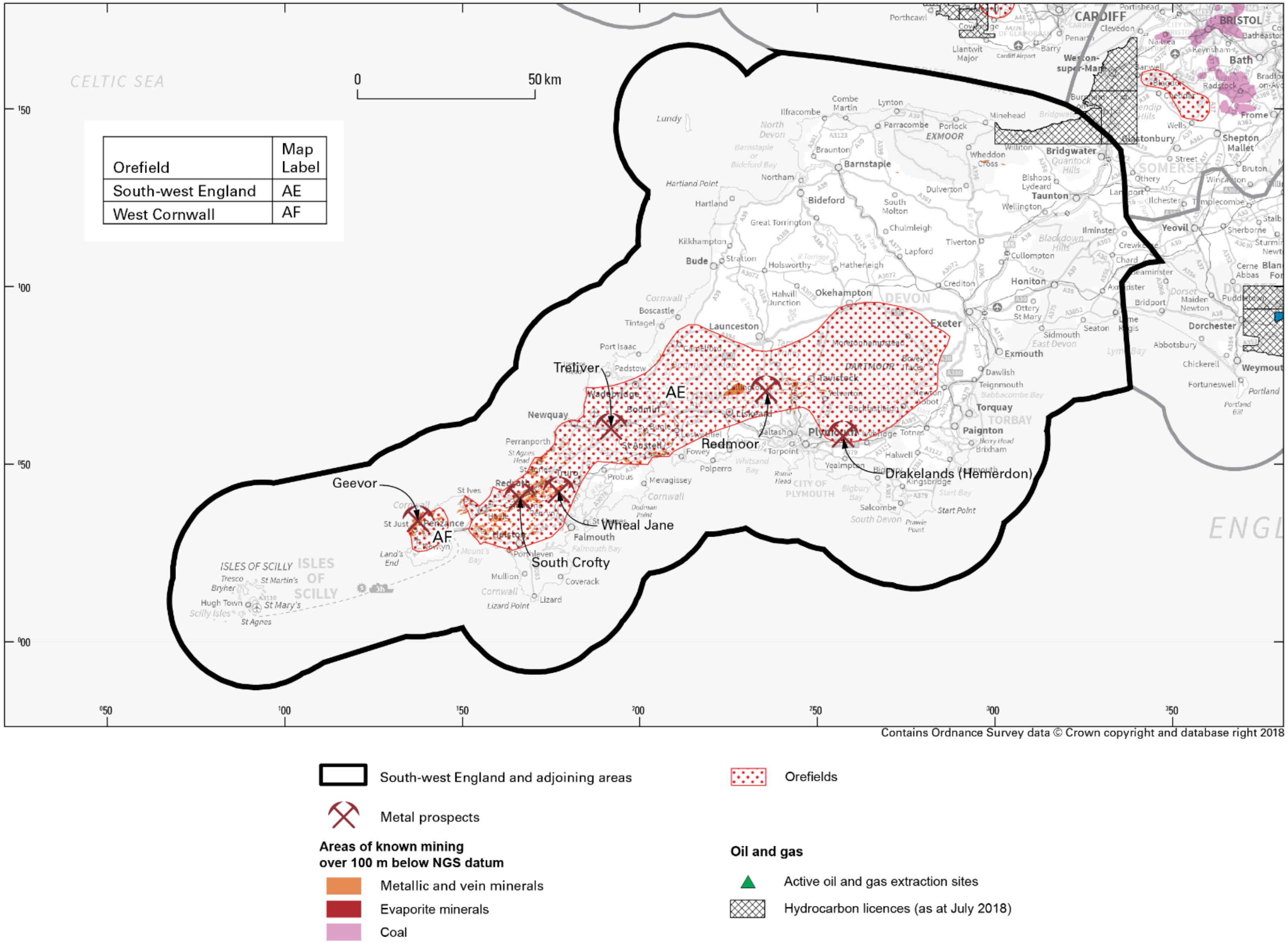

Figure 35 Distribution of mineral resources in the South-west England region. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and 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

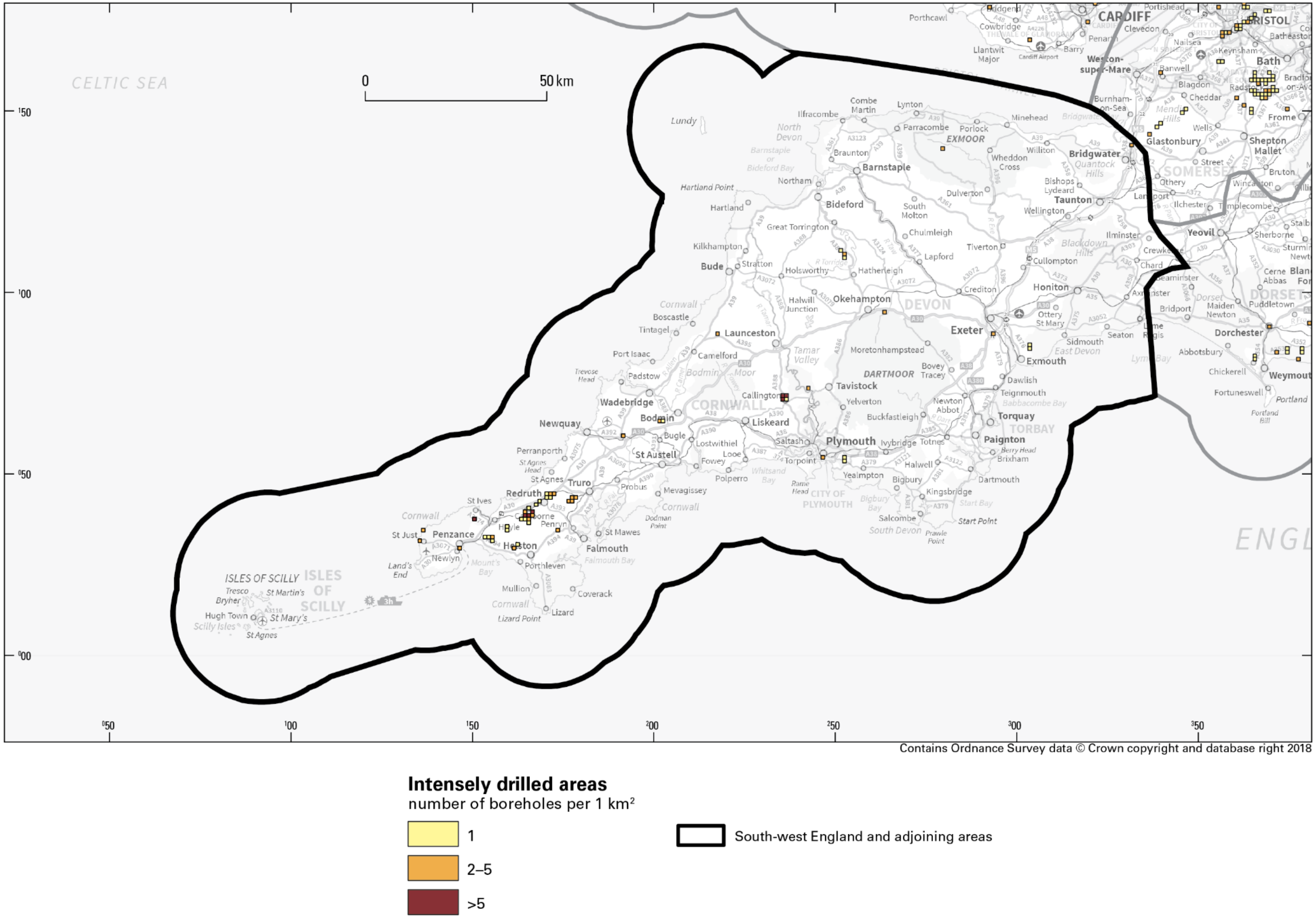

Figure 36 Location of intensely drilled areas in the South-west England region, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

8.11 SUPPORTING INFORMATION

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 Roman times. With such a long history, mines may exist which have not been identified and therefore 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 in the South-west England region is often difficult to attribute to a specific datum. This results in a degree of uncertainty about the maximum depths of workings. For example, Dines (1956) reports depths variously from the surface, adit (or adits), sea level and high water mark but is often unclear which specifically 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. A pragmatic solution to this issue has been to assume that reported depths are to the bottom of the deepest adit unless otherwise stated. Adits were driven from nearby valleys and another reasonable assumption is that adit level is approximately equal to NGS datum at the mine site.

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 overestimate depths where this is not the case.

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 35 have been depicted where possible by applying a 100 m-wide buffer to the mapped extent of the vein. Where this is not possible, a buffer has been applied to the location of known mines in order to encompass the 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 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 extent and distribution of these bedded evaporate deposits is largely based on geological interpretation supported by seismic survey information and occasional boreholes. As such there is uncertainty about their distribution, which in some areas may be considerable.

8.11.4 Coal and related commodities

Coal horizons within the late Carboniferous are steeply dipping and faulted. While the location and extent of past pigment-mining activities are well known, the lateral and vertical extents of these poor-quality coal seams are less well known.

The lignite deposits are known to extend below the 100 m NGS datum depth and are constrained by the extents of the Bovey and Petrockstowe basins. They are low-grade fuels and are not currently considered to be an economic resource.

8.11.5 Borehole depths

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

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

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