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National Geological Screening: Wales

Minerals and Waste Programme

Commissioned Report CR/17/094

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/094

National Geological Screening: Wales

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

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

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Acronyms and abbreviations

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

Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

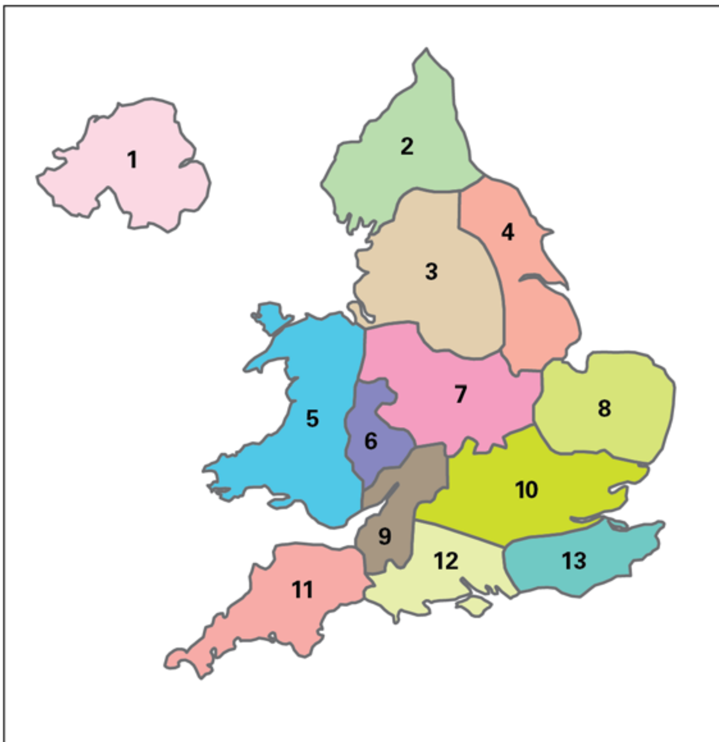
Principal aquifer — a regionally important aquifer defined by the Environment Agency as layers of rock that have high intergranular and/or fracture permeability, meaning they usually provide a high level of water storage (Environment Agency, 2013).

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

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

1 Introduction

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

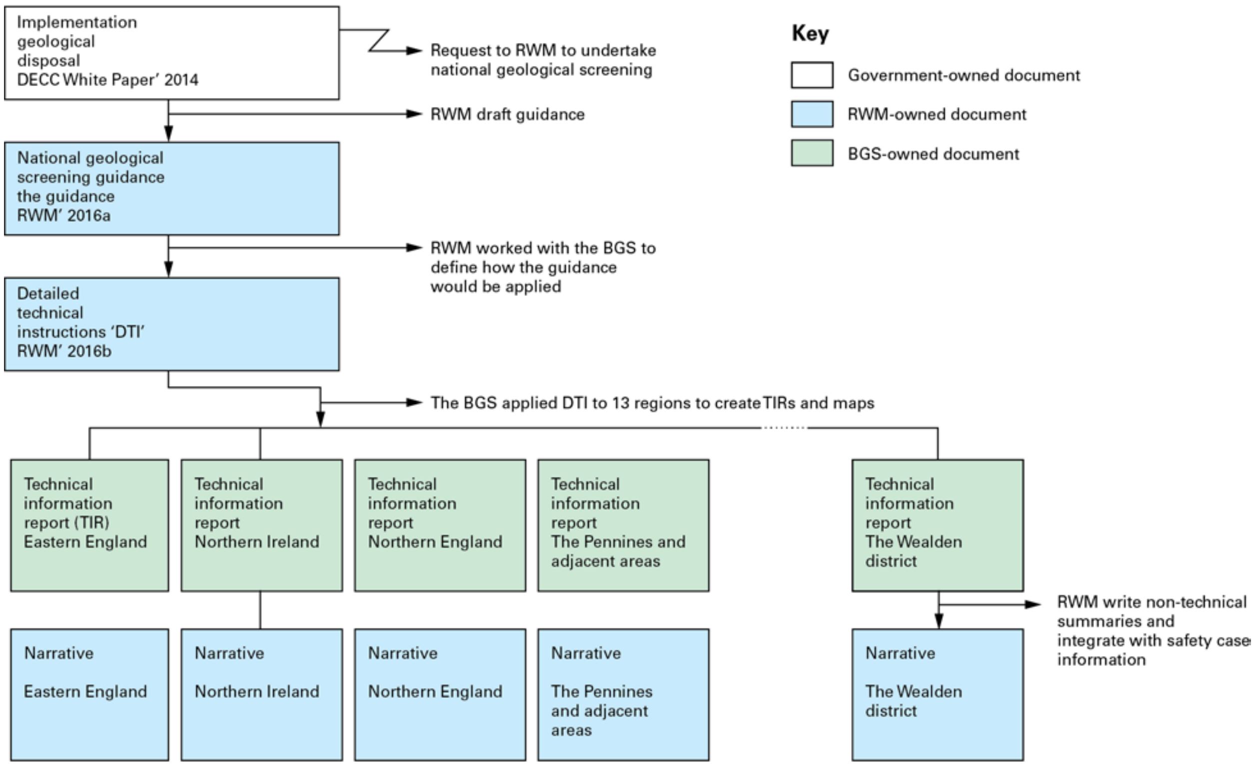


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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 Wales

Wales comprises 22 principal areas (Figure 3) and contains a diversity of rock types, ranging in age from the Precambrian to the Neogene. Across much of Wales the rocks are concealed beneath a patchy cover of superficial deposits, particularly in the valleys, the low-lying coastal tracts and offshore; notable exceptions include the Black Mountains, the coastal strip of the Vale of Glamorgan and Pembrokeshire south of the Preseli Hills.

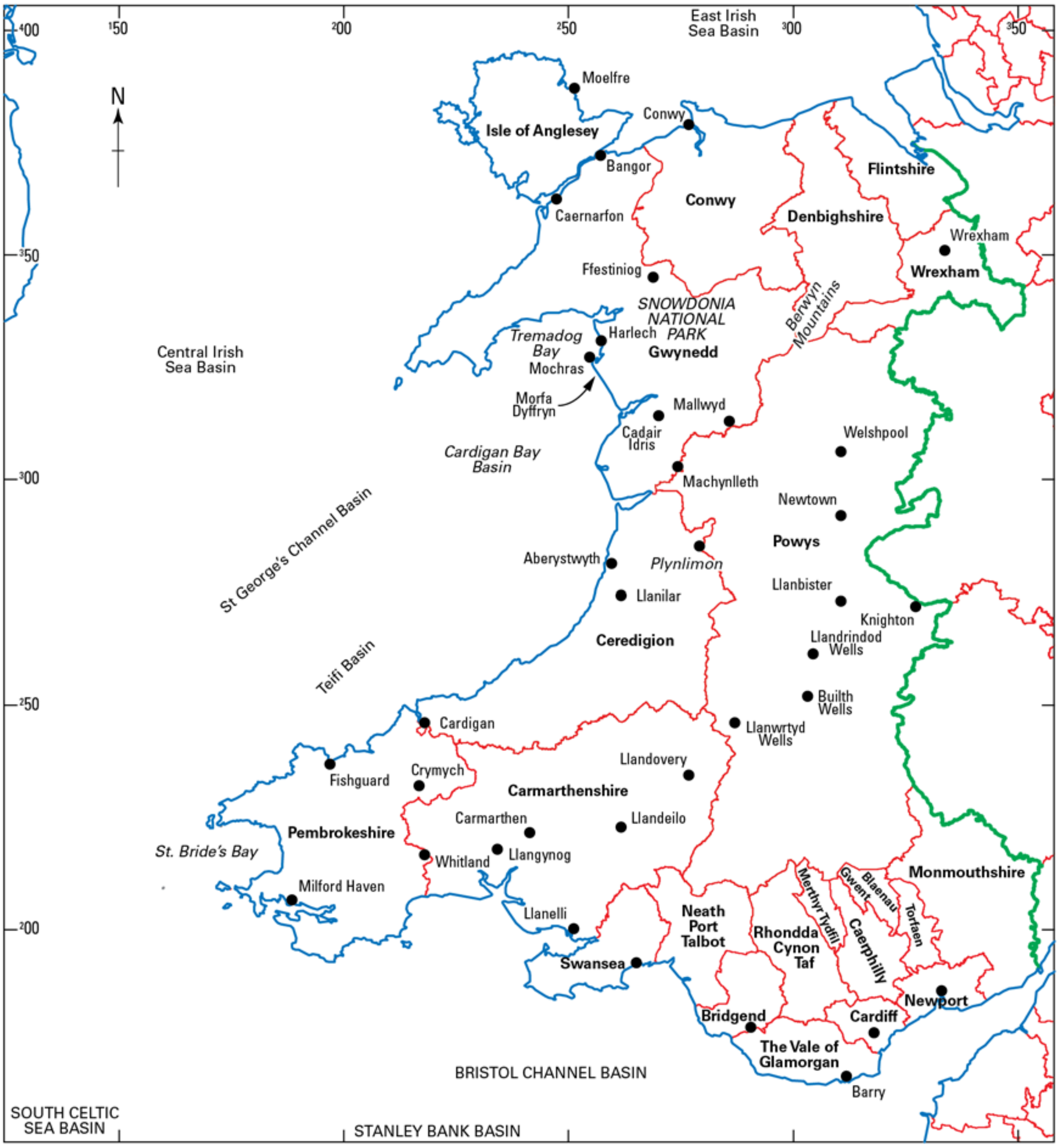


Figure 3 Principal areas of Wales. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290.

The geology has mostly been determined from 1:10 000 or 1:25- 000 scale (or equivalent) geological mapping; such data exists for the majority of the area, though its vintage varies. The near-surface geology is well constrained due to extrapolation from exposures and from shallow boreholes, which have their greatest density in South Wales. In contrast, the geology at depth is not well known because there is a paucity of deep boreholes and geophysical survey data; it should therefore be treated with a lower level of confidence. The BGS records show that there are only 32 boreholes drilled below 1000 m depth in Wales, and a very limited number of seismic reflection lines with published interpretations (Figures 8, 9 and 10). Onshore, the Mesozoic and Cenozoic younger sedimentary rocks are locally well constrained at outcrop by geological mapping, but are more crudely constrained offshore. Their distribution at depth is known with a relatively low level of confidence as they are only proven in shallow boreholes, a limited number of deep boreholes and some seismic reflection surveys (Tappin et al., 1994).

3.1 OVERVIEW OF THE GEOLOGY OF WALES

The geology at surface in Wales is shown in Figure 4 and Figures 5, 6 and 7 illustrate the geological variation across the area. 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 Wales 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 extent of the Wales areas reflects the extent in the BGS Regional Guide series and differs from the formal administrative extent of the country as shown in Figure 3. The reader is referred to the adjacent Bristol and Gloucester region. Welsh Borderlands region and Central England region companion reports for areas of Wales that lie outside the BGS Regional Guide series boundary.

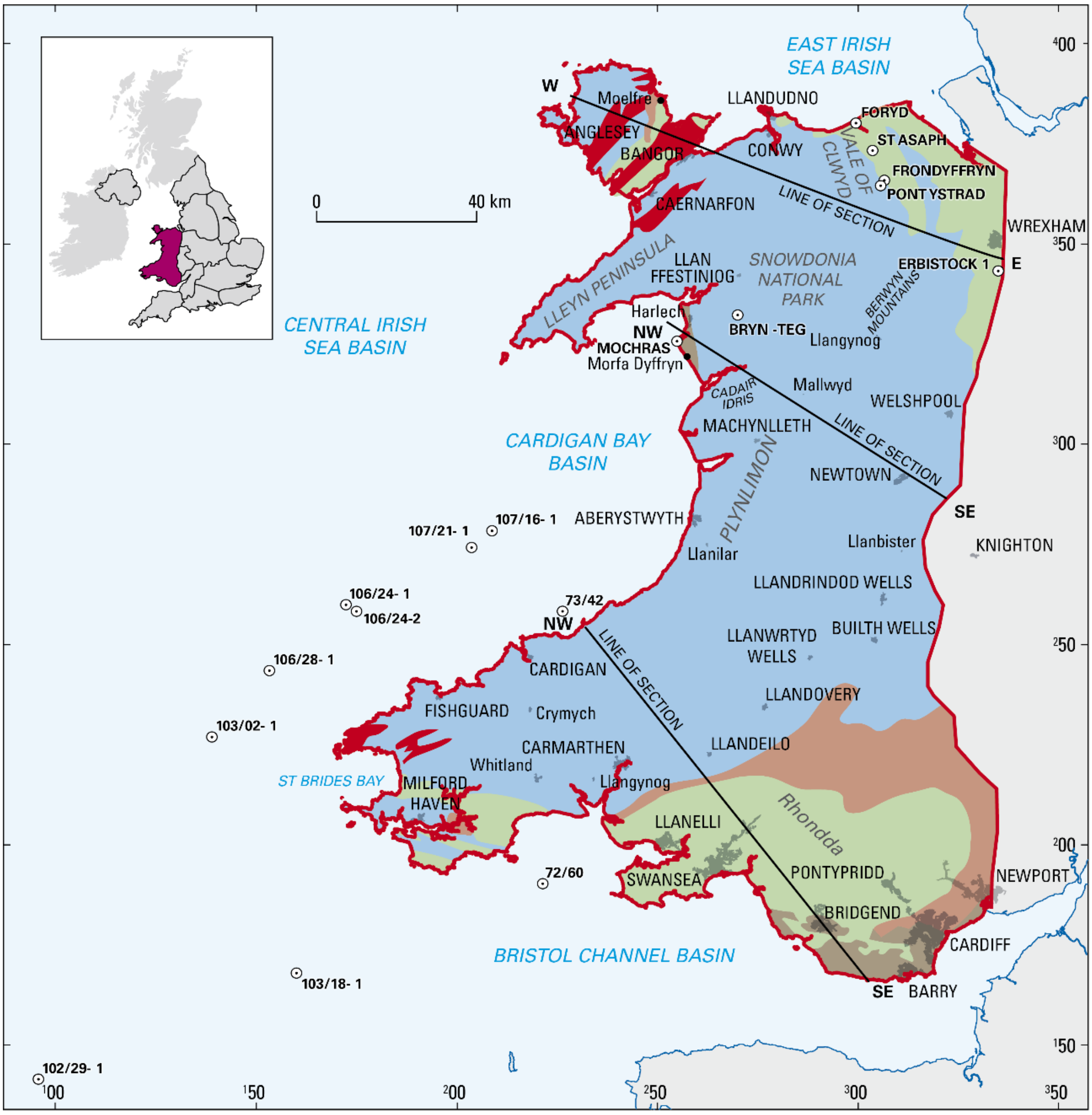
The rocks exposed at surface in Wales and inferred to be present in the depth range of interest for this study are predominantly sedimentary in origin, although extrusive lavas and tuffs, igneous intrusions and small areas of highly metamorphosed rocks are also present. Strata of younger sedimentary rocks (Figure 4) of Eocene to Miocene age are poorly consolidated and largely confined to offshore, where they occupy a series of fault-bounded basins. The underlying Jurassic strata are limited onshore to the coastal strip of south-east Wales, but they expand considerably offshore.

Older sedimentary rocks of Triassic and Permian age also have a limited onshore presence, except for in the north-east of Wales, but they too expand considerably offshore. The underlying Carboniferous and Devonian strata form a broad swathe in South and south-east Wales, from Milford Haven to Monmouth, as well as parts of eastern Anglesey and the Vale of Clwyd. This cover succession overlies a thick sequence of older, early Palaeozoic basement rocks that crop out across most of Mid and North Wales in a broad arc that extends from St. Bride’s Bay to Anglesey.

The distribution of basement rocks at depth is inferred almost entirely from extrapolation of surface outcrop, and confidence levels will consequentially decrease in areas of greater structural complexity. The strata are dominated by basinal turbidite deposits that vary considerably in terms of their mudstone, siltstone, sandstone and conglomerate contents, the proportions of which have allowed different formations (and members) to be defined. Internally, the mudstone facies vary from laminated to massive, and bedding thickness varies from thin (centimetre scale) to medium (decimetre scale) to thick (metre scale); these definitions are used in the descriptions of each rock unit in this report. Detailed mapping has revealed complex internal architectures within each turbidite system, and complex spatial relationships between coeval turbidite sequences. These were, at least in part, controlled by irregularities in the sea floor topography at the time of deposition. For instance, dramatic facies changes are common across the sites of syndepositional faults, and coarse-grained sediments may be confined to submarine channels. The combination of these factors makes predicting spatial variations difficult, although major coarse-grained successions have been defined as separate mapped units. Along the eastern margin of Wales, and particularly within Silurian strata, calcareous mudstones and limestones become more important. Across much of south-east Wales, the uppermost part of the basement rocks consists of Pridoli strata.

Thick successions of indurated volcanic rock are interbedded with the Ordovician turbidites in Pembrokeshire, the Snowdonia massif and on the Llŷn Peninsula. These are predominately of acid and intermediate composition, but include some basic components and are typically accompanied by intrusive bodies of variable size. The volcanic deposits were sourced from a small number of centres, with the products of coeval centres showing complex interfingering relationships. Generally, however, the deposits thin progressively away from their respective centres.

Cambrian strata crop out in southern Snowdonia and in smaller areas in north Snowdonia and Pembrokeshire. These rocks generally include a greater proportion of sandstone than the overlying Ordovician rocks, particularly in Pembrokeshire. On Anglesey and the north-west coast of the Llŷn Peninsula, parts of the Cambro-Ordovician succession have been thrust over younger strata and are represented by a diverse suite of deformed metasedimentary rocks. Locally, small areas of the Proterozoic basement are exposed at the surface in Wales.



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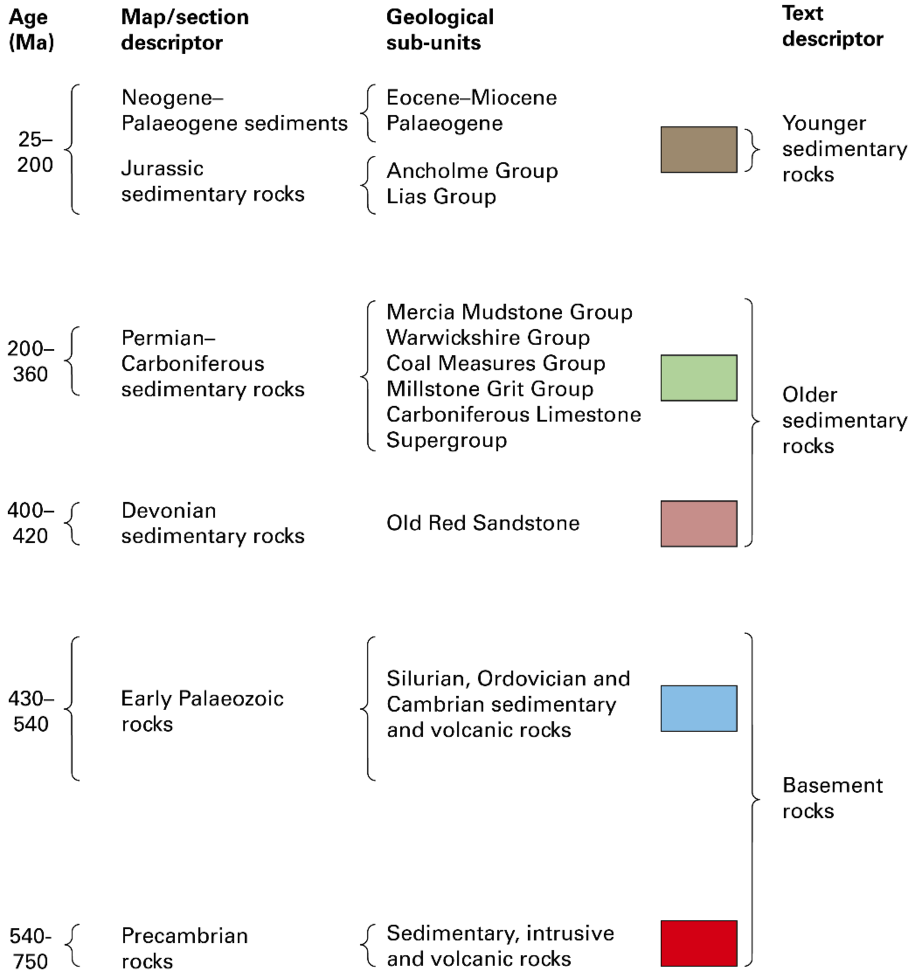


Figure 4 Generalised geological map and key showing the distribution of younger sedimentary rocks, older sedimentary rocks and basement rocks in Wales. The inset map shows the extent of area described in this report, in the UK. See Figures 5, 6 and 7 for schematic cross-sections. The 'Geological sub units' column is highly generalised and does not represent all geological units in the area. 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.

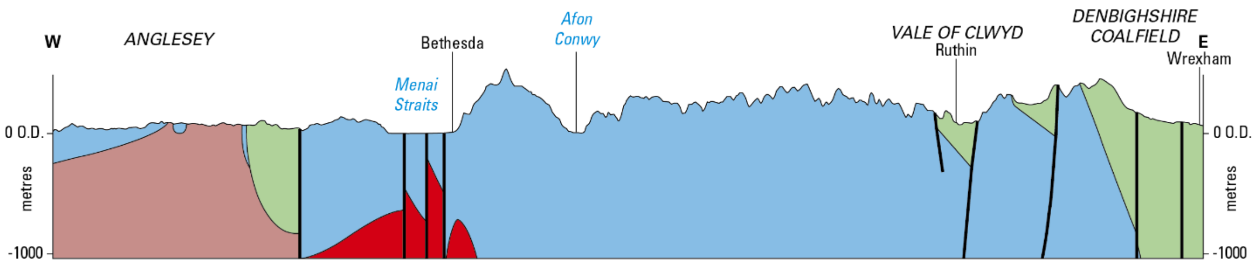


Figure 5 Northern schematic north-west to south-east cross-section through Wales. Line of the section and key are shown in Figure 4. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

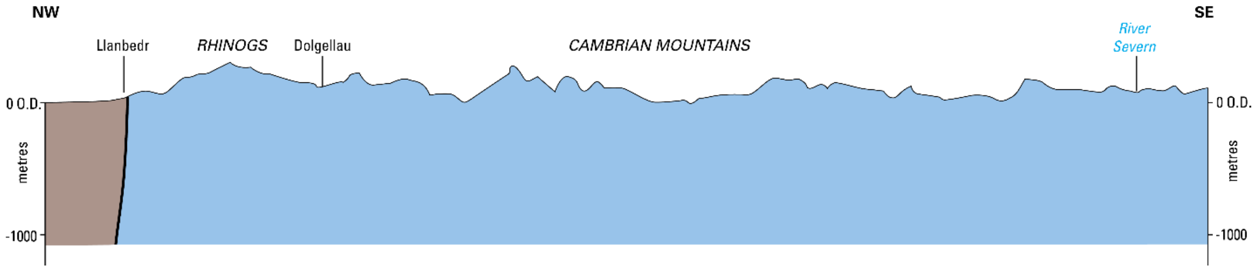


Figure 6 Central schematic north-west to south-east cross-section through Wales. Line of the section and key are shown in Figure 4. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

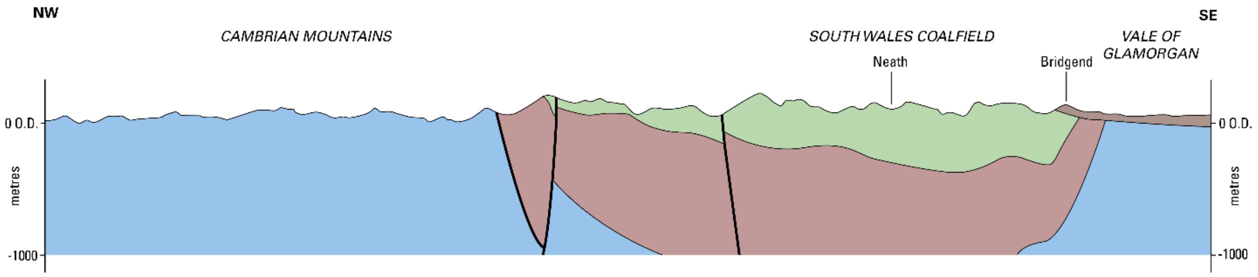


Figure 7 Southern schematic north-west to south-east cross-section through Wales. Line of the section and key are shown in Figure 4. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

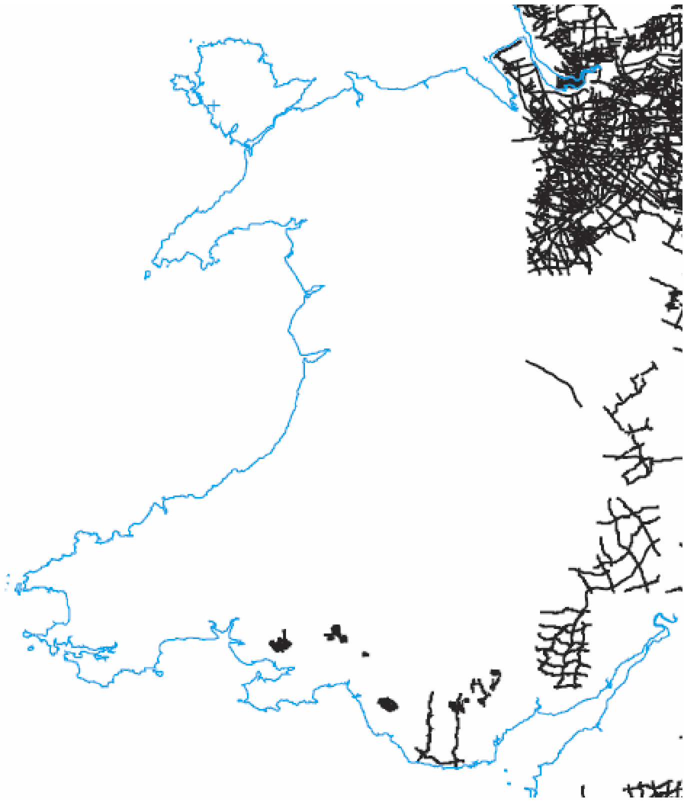


Figure 8 Onshore seismic reflection lines in Wales; taken from Chadwick and Evans (2005), Fig. 2. Note some additional seismic lines have been acquired since 2005 - see https://ukogl.org.uk/. British Geological Survey © UKRI 2018.

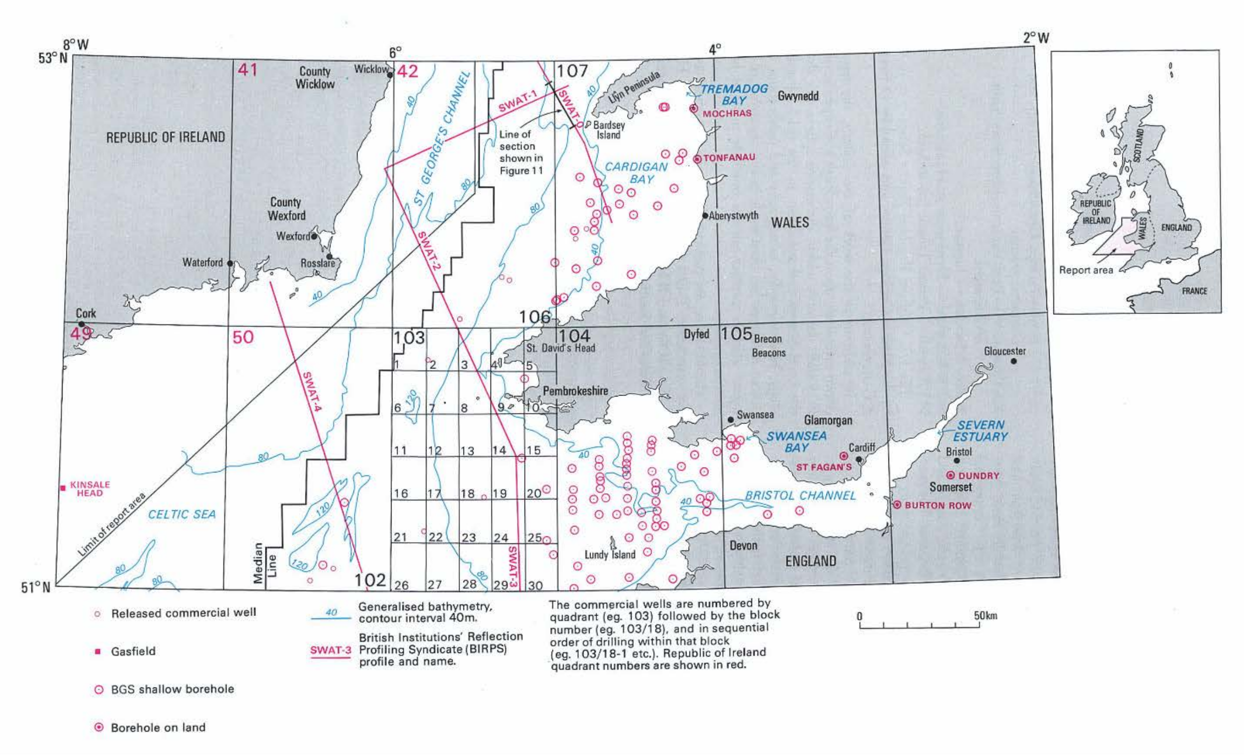


Figure 9 Locations of offshore seismic reflection profiles and released boreholes in the Irish Sea and Bristol Channel; taken from Tappin et al. (1994), Fig. 1. See https://ukogl.org.uk/ for data released since 1994. British Geological Survey © UKRI 2018.

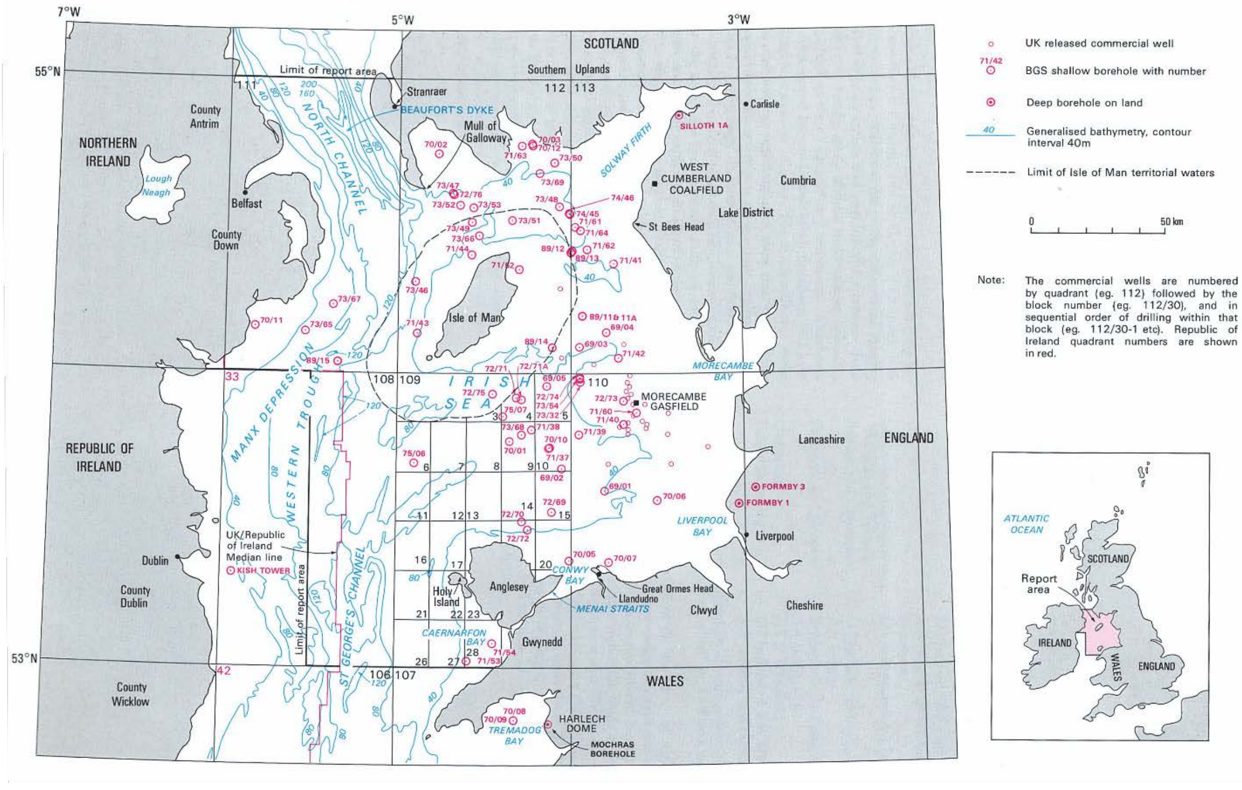


Figure 10 Locations of released boreholes offshore of North Wales; taken from Jackson et al. (1995), Fig. 1. See https://ukogl.org.uk/ for data released since 1995. British Geological Survey © UKRI 2018.

4 Screening topic 1: rock type

4.1 OVERVIEW OF 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 WALES

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

For Wales, the GVS groups the rocks into three age ranges: younger sedimentary rocks (Neogene, Palaeogene and Jurassic) older sedimentary rocks (Triassic, Permian, Carboniferous and Devonian), and basement rocks (early Palaeozoic and Proterozoic). 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 evaporite (EVAP) PRTI in the younger and older sedimentary rocks as well as higher strength rock (HSR) PRTIs in the basement rocks.

Those mudstone-dominated successions that are considered to be HSRs have all been subject to varying degrees of deformation and low-grade metamorphism (epizone and anchizone) during the Acadian Orogeny, and have a pervasive slaty cleavage microfabric. The extent of the cleaved facies has been taken to be approximately coincident with anchizone, or higher, grade metamorphic rocks, as illustrated in Figure 15 (Howells, 2007), but is not well known in detail.

Undivided Permian rocks are confined to the southern end of the St George's Channel basin, offshore of Pembrokeshire. They are entirely below the depth range of interest and are not discussed further. Late Devonian rocks are dominated by interbedded sandstone and conglomerate facies and are not considered further.

The PRTIs are described in Table 3 in stratigraphical order from youngest to oldest (i.e. in downward succession), grouped by the three age ranges: younger sedimentary rocks, older sedimentary rocks and basement rocks. The descriptions include the distribution of the PRTI at surface (outcrop) and where the PRTI is present below the surface (subcrop) within the depth range of interest, along with key evidence for the interpretations. The main geological properties of the PRTIs and how these vary across Wales are also summarised. Data are mostly taken from the BGS publications and other published sources (see references). They may include terminology or nomenclature that has been updated since those publications were released. The term 'mudstone' follows BGS usage to include claystone and siltstone-grade siliciclastics (Hallsworth and Knox, 1999). The location of boreholes referred to in this chapter is shown on Figure 4.

Maps showing the generalised distribution of PRTIs between 200 and 1000 m below surface, amalgamated into the generic host-rock types are provided in Figures 11, 12 and 13, respectively. A further map showing the generalised combined lateral distribution of all PRTIs is provided in Figure 14.

Table 3 Schematic GVS for Wales 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 11, 12, and 13 for the distribution of PRTIs amalgamated by host rock model (i.e. LSSR, HSR and EVAP respectively).

Geological period		Geological unit identified in NGS3D	Dominant rock type	Potential rock types of interest			Principal aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS	Neogene	Eocene to Miocene rocks (undivided)	Conglomerate, sandstone, siltstone and claystone	N/A	'Transitional series'	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Palaeogene	Palaeogene rocks (undivided)	Sandstone, siltstone, conglomerate and claystone	N/A	Palaeogene rocks	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Kimmeridge Clay Formation	Mudstone, limestone and sandstone	N/A	Kimmeridge Clay Formation	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Corallian Group	Limestone, sandstone, mudstone and siltstone	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Upper Jurassic rocks (undivided)	Calcareous mudstone, siltstone and sandstone; subordinate limestone	N/A	Kimmeridge Clay Formation	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Kellaways and Oxford Clay formations	Calcareous and silty mudstone, and sandstone	N/A	Kellaways and Oxford Clay formations	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Great Oolite Group	Mudstone and bioclastic and ooidal limestones; subordinate calcareous sandstone	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Inferior Oolite Group	Sandstone, limestones; subordinate ooidal limestone, siltstone and mudstone	N/A	N/A	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Mid Jurassic rocks (undivided)	Sandstone, siltstone, limestone and mudstone	N/A	Kellaways and Oxford Clay formations	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Jurassic rocks (undivided)	Mudstone, sandstone, siltstone and limestone, interbedded	N/A	Kellaways and Oxford Clay formations; Lias Group	N/A	N/A
YOUNGER SEDIMENTARY ROCKS	Jurassic	Lias Group	Mudstone, variably calcareous, interbedded with siltstone and subordinate limestone	N/A	'Upper Lias', 'Lower Lias Clay', Blue Lias Formation	N/A	N/A
OLDER SEDIMENTARY ROCKS	Triassic	Sidmouth Mudstone Group	Silty mudstone, dolomitic mudstone and evaporites	N/A	Sidmouth Mudstone Formation	Preesall Halite, Northwich Halite and Wilkesley Halite members	N/A
OLDER SEDIMENTARY ROCKS	Triassic	Mercia Mudstone Group, including Penarth Group	Silty mudstone with interbedded siltstone, dolomite and evaporite deposits of gypsum, halite and anhydrite	N/A	Mercia Mudstone Group, including Penarth Group	Unnamed halite, Mercia Mudstone Group	Mercia Mudstones Group marginal facies
OLDER SEDIMENTARY ROCKS	Triassic	Sherwood Sandstone Group	Sandstone, subordinate siltstone, breccia and mudstone	N/A	N/A	N/A	Sherwood Sandstone Group
OLDER SEDIMENTARY ROCKS	Triassic	Triassic rocks (undivided)	Silty mudstone, siltstone, dolomite and evaporites	N/A	Mercia Mudstone Group	N/A	N/A
OLDER SEDIMENTARY ROCKS	Permian	Cumbrian Coast Group	Interbedded evaporites, mudstone, siltstone, sandstone, and dolomite; subordinate breccia	N/A	Cumbrian Coast Group	N/A	N/A
OLDER SEDIMENTARY ROCKS	Permian	Appleby Group	Sandstone and conglomerate	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Permian	Permian rocks (undivided)	Interbedded mudstone, sandstone and conglomerate	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Warwickshire Group	Interbedded mudstone and sandstone; subordinate seatearth, coal and limestone	N/A	Warwickshire Group	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	South Wales Upper Coal Measures Group	Mudstone and siltstone; subordinate sandstone, coal and seatearth	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Pennine and South Wales Middle and Lower Coal Measures formations	Mudstone, siltstone, and sandstone; subordinate coal, ironstone and seatearth	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Pennine Coal Measures Group	Sandstone, siltstone and mudstone; subordinate coal, ironstone and seatearth	N/A	N/A	N/A	N/A

OLDER SEDIMENTARY ROCKS	Carboniferous	Marros Group	Mudstone and sandstone; subordinate chert, conglomerate and siltstone	N/A	N/A	N/A	N/A
		Millstone Grit Group	Feldspathic sandstone interbedded with siltstone and mudstone; subordinate coal and seatearth	N/A	N/A	N/A	N/A
		Craven Group	Mudstone and limestone packstone and wackestone	N/A	N/A	N/A	N/A
		Tournaisian–Visean = Carboniferous Limestone Supergroup	Limestone, locally dolomitised; subordinate sandstone and argillaceous rocks	N/A	N/A	N/A	Carboniferous Limestone Supergroup
	Devonian	Late Devonian rocks (undivided)	Sandstone and conglomerate; subordinate siltstone and mudstone	N/A	N/A	N/A	N/A
		Early Devonian rocks (undivided)	Conglomerate, sandstone and calcretised muddy siltstone, weakly cleaved; subordinate limestone	Traeth Bach Formation	N/A	N/A	N/A
		Devonian rocks (undivided)	Sandstone, siltstone, mudstone and conglomerate; subordinate limestone	N/A	N/A	N/A	N/A
BASEMENT ROCKS	Early Palaeozoic	Pridoli rocks (undivided)	Calcretised muddy siltstone; subordinate conglomerate, sandstone and limestone	N/A	N/A	N/A	N/A
		Ludlow rocks (undivided)	Mudstone, silty mudstone, mudstone and muddy sandstone, locally cleaved	Elwy Formation	N/A	N/A	N/A
		Wenlock rocks (undivided)	Mudstone, silty mudstone, mudstone and muddy sandstone, locally cleaved	Nantglyn Flags and Nant Ysgollon Mudstone formations	N/A	N/A	N/A
		Llandovery rocks (undivided)	Mudstone, silty mudstone, mudstone and muddy sandstone, locally cleaved	Llandovery rocks	N/A	N/A	N/A
		Silurian rocks (undivided)	Limestone, mudstone and sandstone	N/A	N/A	N/A	N/A
		Ashgill rocks (undivided)	Mudstone, well cleaved; subordinate sandstone, and mudstone	Yr Allt and Nantmel Mudstone formations; Ashgill rocks (undivided)	N/A	N/A	N/A
		Caradoc rocks (undivided)	Mudstone, well cleaved, intervening siltstone and mudstone	Drefach Group; Caradoc rocks (undivided)	N/A	N/A	N/A
		Llanvirn rocks (undivided)	Mudstone, well cleaved, subordinate sandstone and comglomerate; volcanic rocks locally abundant	Aber Mawr Shale and Abergwilli formations; Nant Ffrancon Subgroup (part); Llanvirn rocks (undivided)	N/A	N/A	N/A
		Arenig rocks (undivided)	Pembrokeshire: mudstone dominated. North Wales: sandstone dominated	Penmaen Dewi Shales Formation	N/A	N/A	N/A
		Tremadoc rocks (undivided)	Silty mudstone, well cleaved; sandstones	Dol-cyn-afon Formation	N/A	N/A	N/A
		Unnamed felsic intrusions, Ordovician to Silurian	Intrusions of massive granite, rhyolite and microtonalite; variably jointed	Unnamed felsic intrusions, Ordovician to Silurian	N/A	N/A	N/A
		Unnamed mafic intrusions, Ordovcian to Silurian	Dolerite, medium-grained, well-jointed	Unnamed mafic intrusions, Ordovician to Silurian	N/A	N/A	N/A
		Ordovician volcanic rocks and sills (undivided)	Heterolithic acidic intrusions, lavas and pyroclastics intercalated with silty mudstones; subordinate basic igneous rocks and tuffaceous sandstone	Fishguard Volcanic, Snowdon Volcanic and Llanbedrog Volcanic groups	N/A	N/A	N/A

BASEMENT ROCKS	Early Palaeozoic	Ordovician felsic lava	Rhyolite lava and breccia; subsidary acidic tuff and siltstone	Conwy Rhyolite Formation	N/A	N/A	N/A
		Ordovician unnamed mafic rocks	Heterolithic mafic tuff and lava	N/A	N/A	N/A	N/A
		Ordovician rocks (undivided)	Interbedded mudstone and sandstone-dominated units, variably cleaved, locally calcareous, sandstone and limestone	Ordovician rocks (undivided)	N/A	N/A	N/A
		Cambrian and Ordovician rocks (undivided)	Silty mudstone and sandstone-dominated units. Local andesitic lavas and tuffs	Cambrian and Ordovician rocks (undivided)	N/A	N/A	N/A
		Late Cambrian rocks, including Tremadoc	Interbedded silty mudstone, siltstone or sandstone	Ffestiniog, Maentwrog and Dolgellau formations	N/A	N/A	N/A
		Late Cambrian metasedimentary rocks, including Tremadoc	Thick anchizone to greenschist-grade mudstone, debrite, sandstone and volcan clastic-dominated units; subordinate metabasic lenses	Holy Island, New Harbour and Gwna groups	N/A	N/A	N/A
		Late Cambrian rocks (undivided)	Sandstone and conglomerate	N/A	N/A	N/A	N/A
		Mid Cambrian rocks (undivided)	Snowdonia: siltstone or silty mudstone, thin sandstones. Pembrokeshire: sandstone and subordinate conglomerate and mudstone	Clogau, Gamlan and Hafotty formations	N/A	N/A	N/A
		Early Cambrian rocks (undivided)	Snowdonia: well-cleaved mudstone, sandstone and conglomerate at base. Pembrokeshire: micaceous sandstone, conglomerate and mudstone	Llanberis Slates and Llanbedr formations	N/A	N/A	N/A
		Cambrian rocks (undivided)	Interbedded mudstone, siltstone, sandstone and conglomerate	N/A	N/A	N/A	N/A
		Early Palaeozoic rocks (undivided)	Interbedded mudstone, siltstone and sandstone; subordinate conglomerate and volcanic rocks	Lower Palaeozoic rocks (undivided)	N/A	N/A	N/A
		Proterozoic to Palaeozoic rocks (undivided)	Varied suite of sedimentary, igneous and metamorphic rocks	N/A	N/A	N/A	N/A
		Unnamed Neoproterozoic extrusive rocks	North Wales: uniform, strongly welded acidic ash-flow tuff. Pembrokeshire: interbedded rhyolitic tuffs breccias and thin lavas	Padarn Tuff Formation; Pebidian Supergroup	N/A	N/A	N/A
		Neoproterozoic rocks (undivided)	Mostly greenschist-grade mix of meta-sediments, volcan clastics, volcanics and intrusions; mudstone and sandstone-dominated sequences locally important. Anglesey: high-grade pelites and subordinate meta sandstones, carbonates and basalts, and fine-grained hornfels	Coedana Complex and the central Anglesey and Berw shear zones	N/A	N/A	N/A
		Avalonian Proterozoic crystalline basement	Granite, grandiorite and bimodal suites of gabbro-diorite	Coedana granite; Twt Hill granite	N/A	N/A	N/A

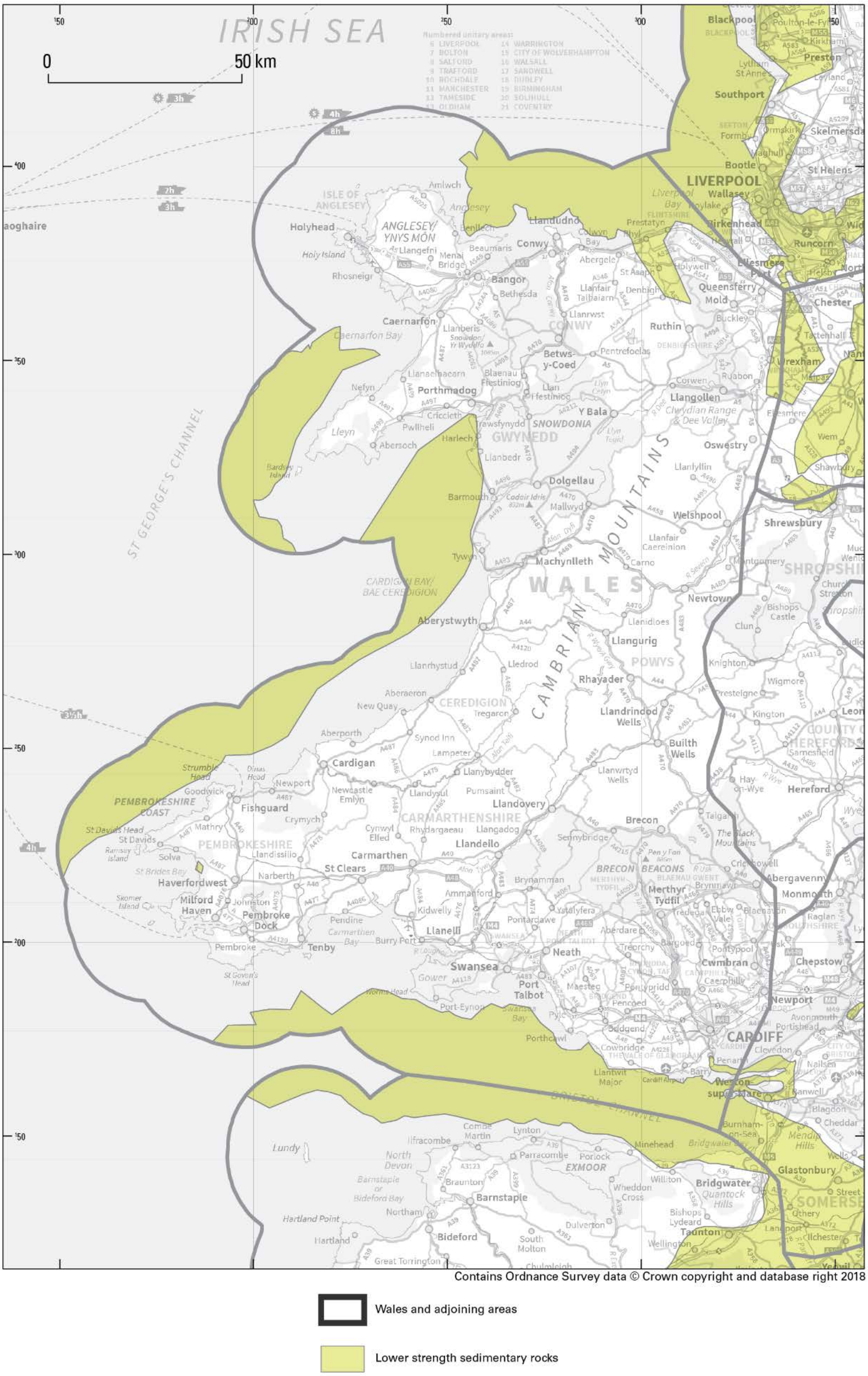


Figure 11 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in Wales. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

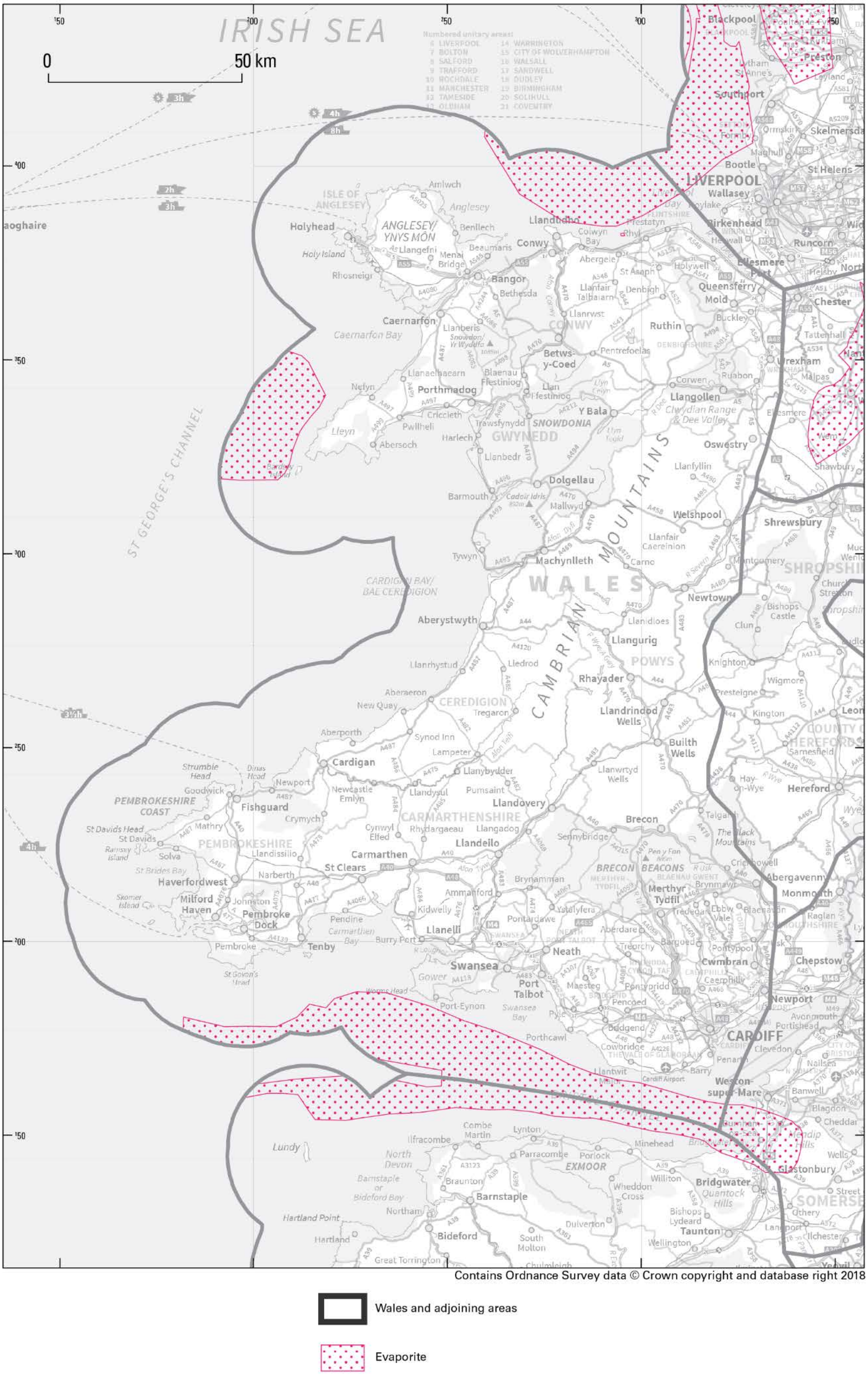


Figure 12 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in Wales. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

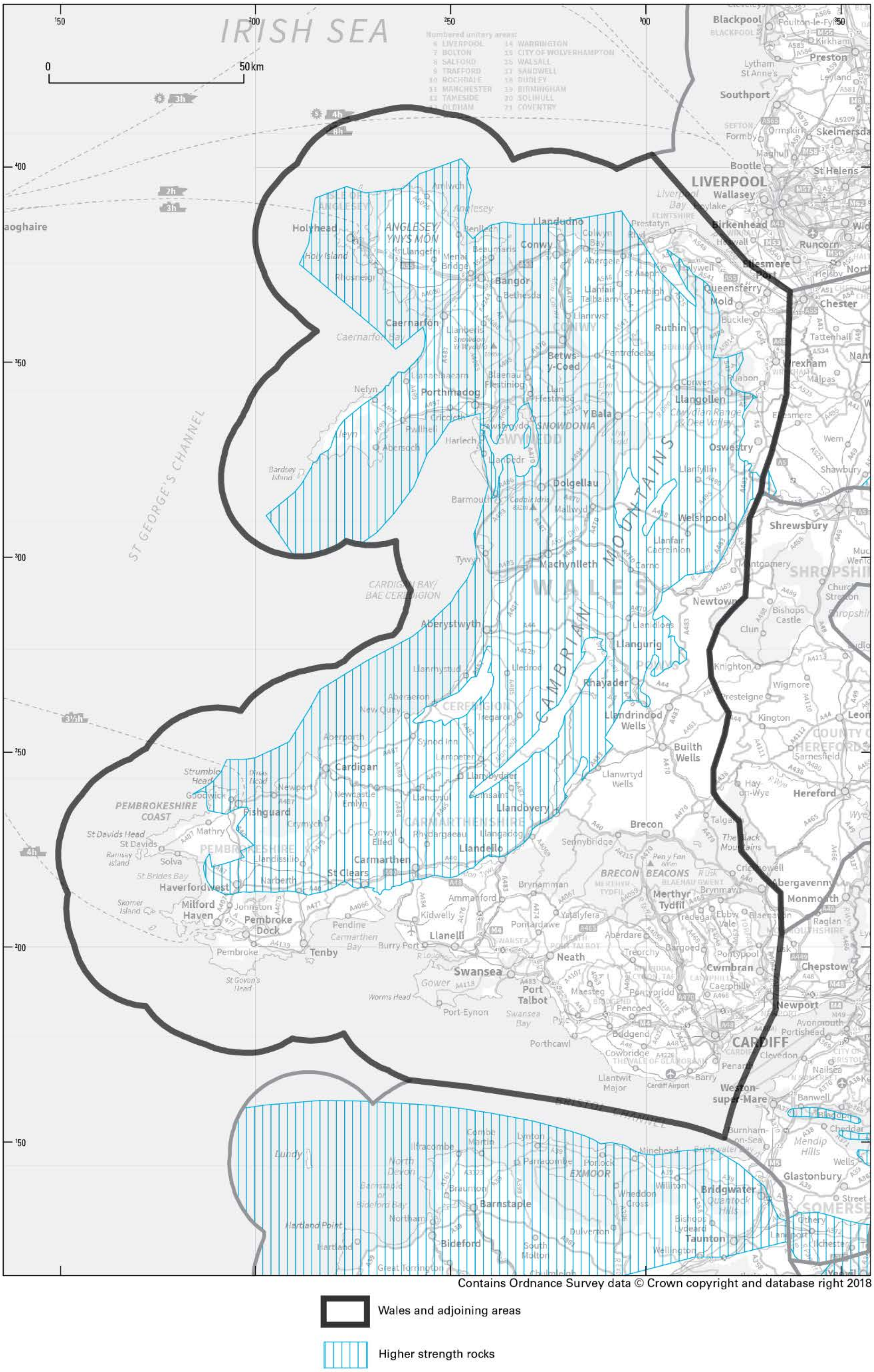


Figure 13 The generalised lateral distribution of HSR at depths of between 200 and 1000 m below NGS datum in Wales. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

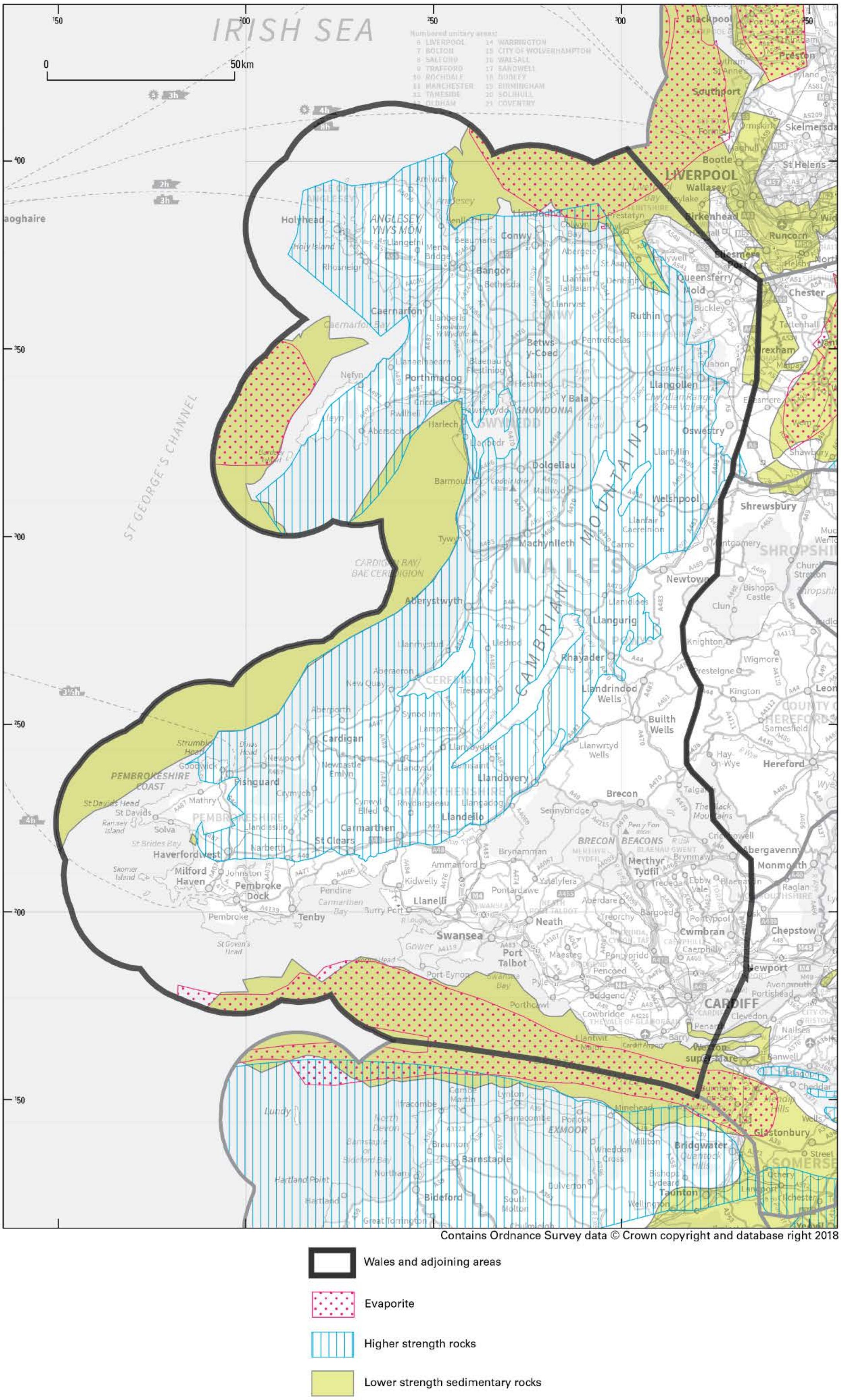


Figure 14 The combined generalised lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in Wales. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

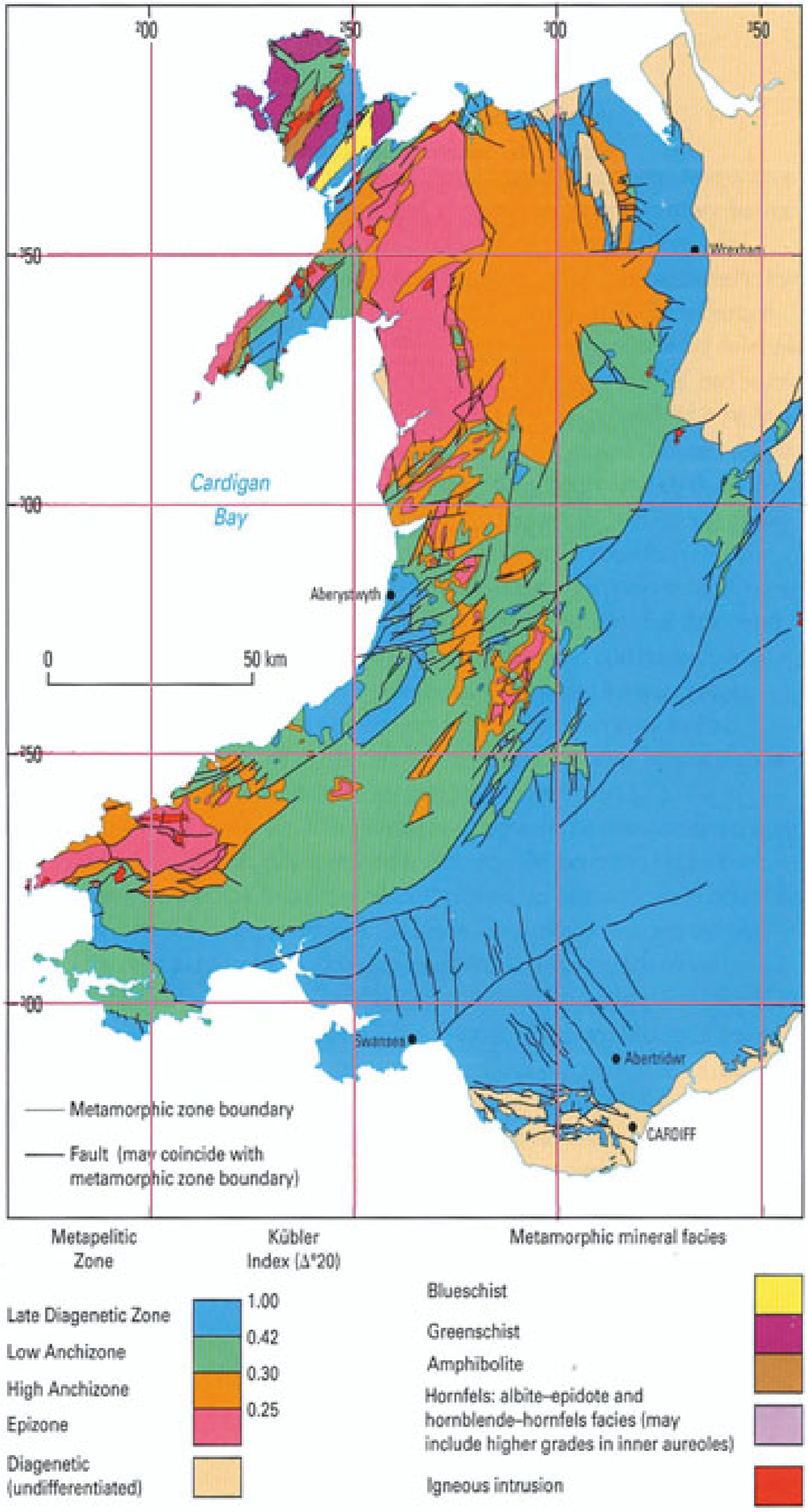


Figure 15 Metamorphic map of Wales showing the extent of HSR at rockhead, as defined by anchizone, or higher, grade metamorphism for mudstone-dominated successions; taken from Howells (2007), Fig. 32. British Geological Survey © UKRI 2018.

4.2.1 Younger sedimentary rocks

4.2.1.1 UNDIVIDED EOCENE TO MIOCENE ROCKS — LSSR

Eocene to Miocene strata occur offshore of Wales in the St George's Channel and Cardigan Bay basins, as well as in the smaller Teifi and Stanley Bank basins (Figure 16), but are only modelled separately in the Cardigan Bay basin. Here, the unit occupies an eastward-dipping half-graben that terminates against major faults, and forms part of a Cenozoic succession that lies with marked unconformity (Figure 17) on Jurassic and Triassic LSSRs, as well as Carboniferous strata. Despite cropping out on the sea floor, much of the unit lies within the depth range of interest.

Miocene rocks are best known from the Mochras Borehole on the eastern margin of the Cardigan Bay basin; three other boreholes penetrate the associated succession, and some interpreted seismic reflection data is available (e.g. Tappin et al., 1994).

Up to 600 m of undivided Eocene to Miocene rocks lie within the Cardigan Bay basin, of which 524 m were sampled in the Mochras Borehole (Figure 18). Its succession may be divided into three parts. The lowest part, approximately 200 m thick, is dominated by cobble-grade conglomerates; the middle part, approximately 120 m thick, is characterised by upward-fining cycles of siltstone and claystone; and the upper part, approximately 200 m thick, consists of upward-fining heterogeneous cycles of sandstone, siltstone, claystone and lignite. Only the middle part ('transitional series'), which is characterised by a more regular gamma ray and sonic velocity signal (Figure 18), is considered a PRTI.

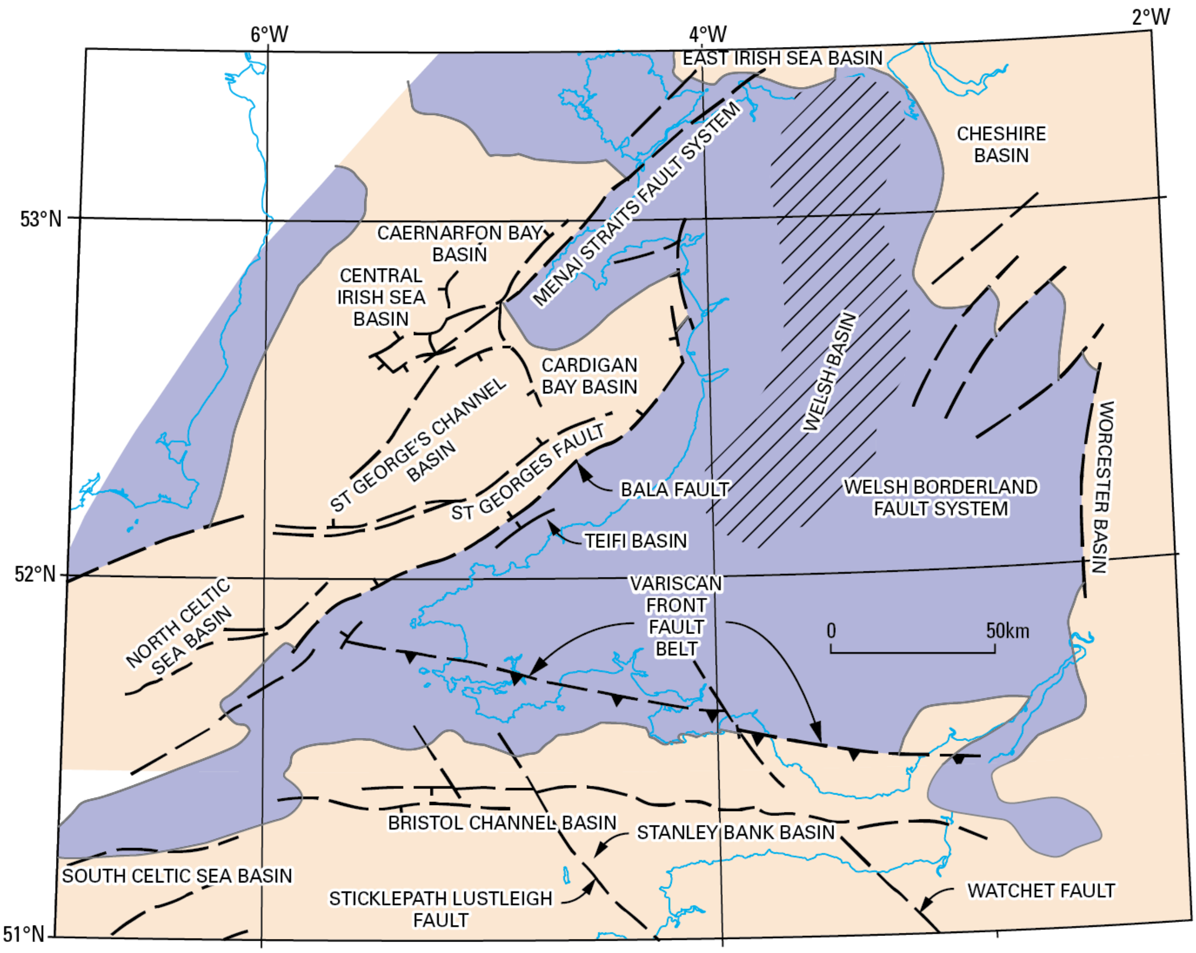


Figure 16 Tectonic map of Wales showing major faults, folds and lineaments; taken from Howells (2007), Fig. 31. British Geological Survey © UKRI 2018.

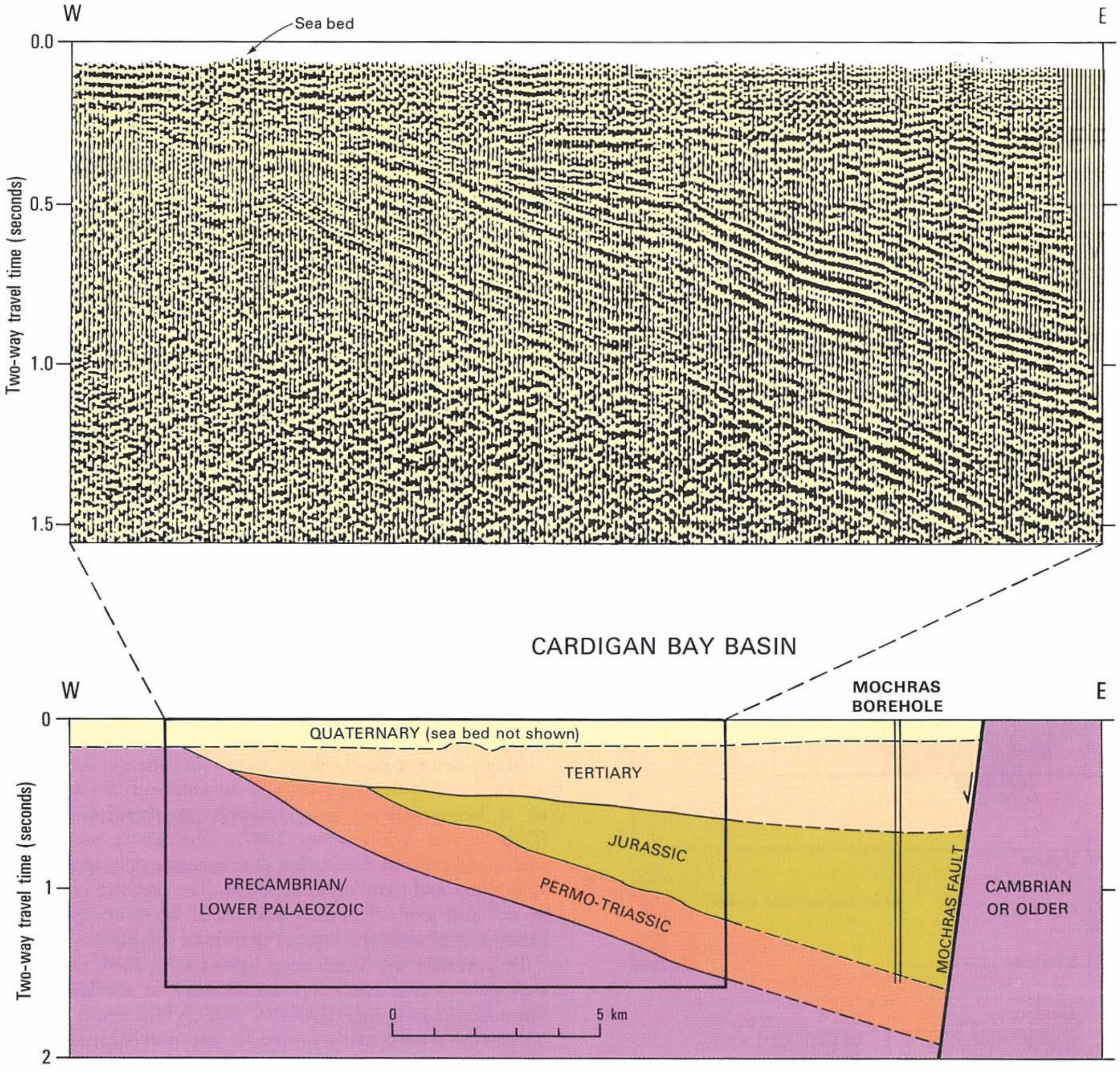


Figure 17 Seismic reflection profile, with interpretation, across part of the Cardigan Bay basin. Cenozoic (Tertiary) rocks occupy a half-graben and lie with marked unconformity on older rocks; taken from Tappin et al. (1994), Fig. 51. British Geological Survey © UKRI 2018.

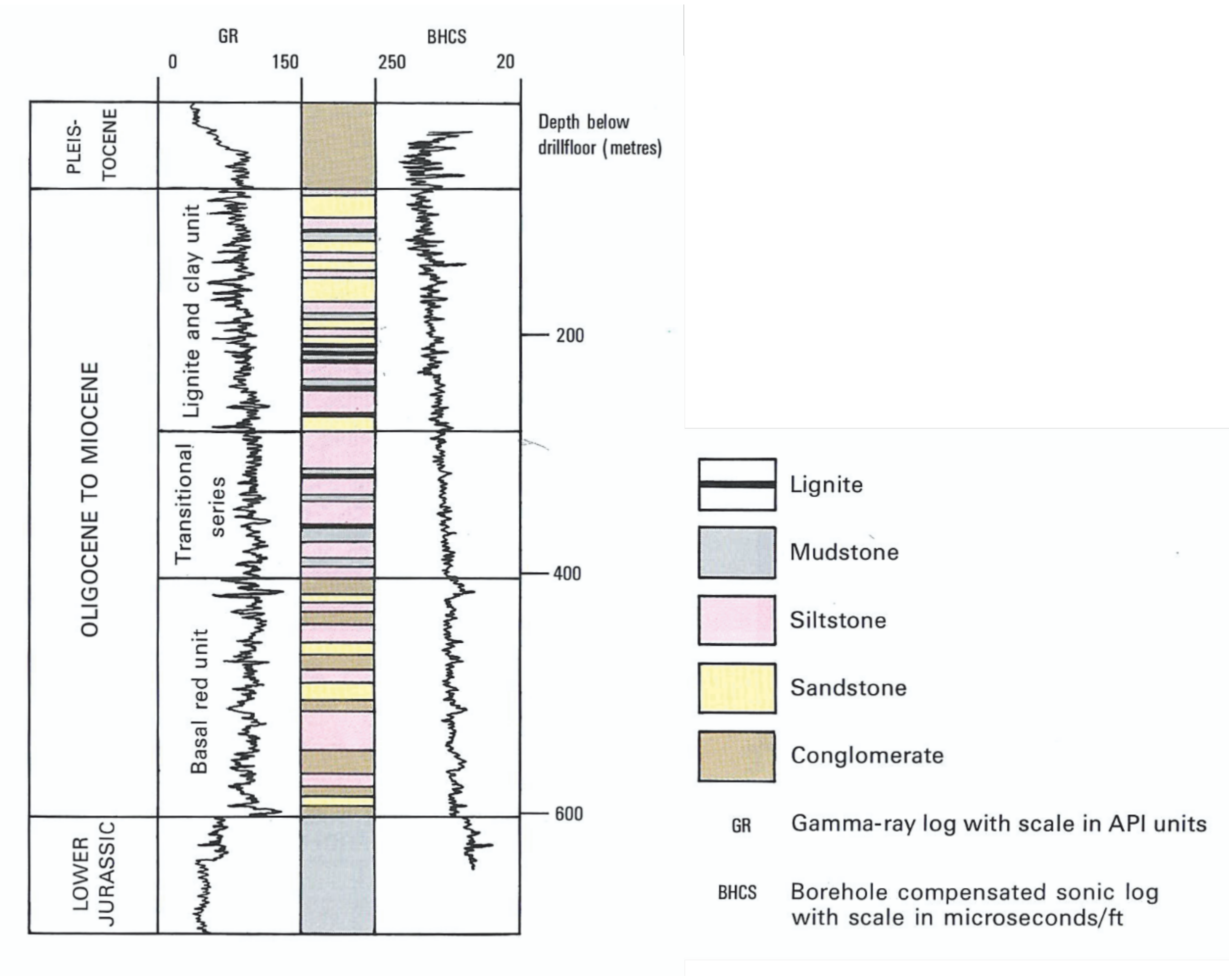


Figure 18 Log of Cenozoic strata in the Mochras Borehole; taken from Tappin et al. (1994), Fig. 50. British Geological Survey © UKRI 2018.

4.2.1.2 Undivided Palaeogene rocks — LSSR

Palaeogene strata occur offshore of Wales in the St George's Channel and Cardigan Bay basins, as well as in the smaller Teifi and Stanley Bank basins (Figure 16), but they are only modelled separately in the southern part of the St George's Channel basin. Here, the unit lies with marked unconformity (Figure 17) on Jurassic and Triassic LSSRs and is bounded to the east by a major fault. The basin is divided into two by the north-east-oriented St. George's Fault (Figure 16), along which a salt wall has been emplaced (Tappin et al., 1994). As well as cropping out on the sea floor, much of the unit lies within the depth range of interest.

Palaeogene strata are well resolved in the limited available seismic reflection data (Tappin et al., 1994), and best known from the Mochras Borehole (Figure 18) on the eastern margin of the Cardigan Bay basin, which penetrated the mid Oligocene to Early Miocene strata (Herbert-Smith, 1979) that are included in the Eocene to Miocene rocks LSSR. Locally, unconformities that are apparent in seismic reflection profiles have been correlated with depositional breaks observed within boreholes (e.g. 106/28-1, Tappin et al., 1994).

Within the St George's Channel basin, over 1500 m of undivided Palaeogene rocks are preserved north-west of the St George's Fault, and over 1000 m to the south-east. They may be subdivided into two parts. The lower part is dominated by sandstone, siltstone and conglomerate, as exemplified by borehole 106/28-1 (Figure 19), whereas the upper part, which forms the bulk of the succession, is finer-grained and consists of a variable mix of decametre-scale beds of silty and sandy claystone, siltstone, sandstone and lignite (up to 100 m thick). Only intervals in the upper part are considered a PRTI, though the log for 106/28-1 should be treated with extreme caution because it has been interpreted from a gamma ray log run behind casing; the presence of lignite has not been confirmed in other logs.

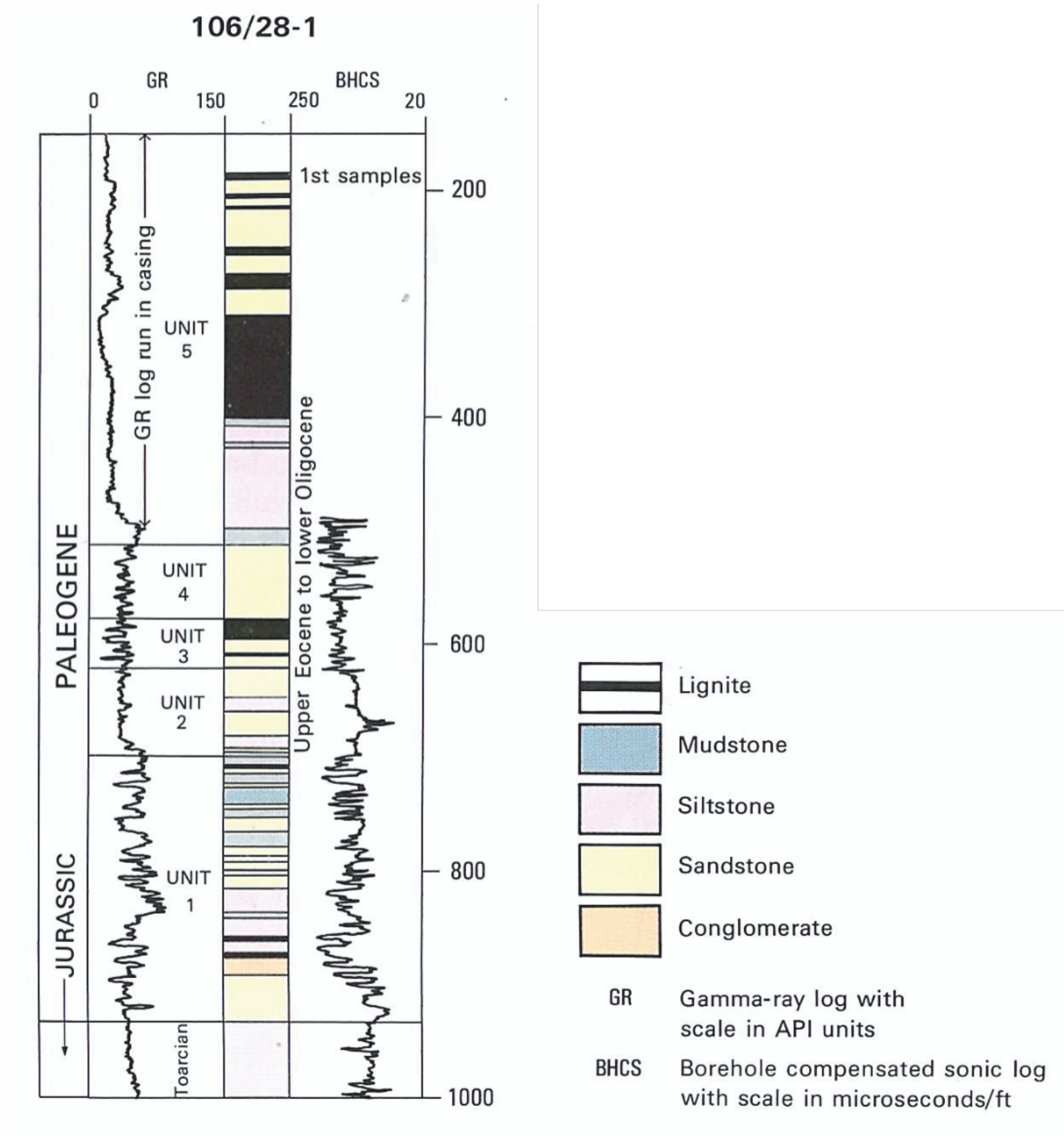


Figure 19 Log of Palaeogene rocks in borehole 106/28-1 in the St. George's Channel basin; taken from Tappin et al. (1994), Fig. 55. British Geological Survey © UKRI 2018.

4.2.1.3 KIMMERIDGE CLAY FORMATION — LSSR

The Kimmeridge Clay Formation locally forms a component part of the undivided Jurassic rocks and the undivided Late Jurassic rocks, both of which are LSSR PRTIs. The unit is also separately modelled in a small area in the southern part of the St George's Channel basin, where it is overlain by undivided Palaeogene rocks and undivided Eocene to Miocene rocks. Here, the unit is bounded to the east by a major fault and/or overstepped by younger strata.

The Kimmeridge Clay Formation is proven in several deep boreholes in the St George's Channel basin (Tappin et al., 1994) and the Bristol Channel basin, as well as shallow BGS boreholes (Tappin et al., 1994). It exhibits a distinctive geophysical log signature, which allows the unit to be confidently correlated with the onshore succession outside Wales.

The thickest successions (up to 958 m) of the Kimmeridge Clay Formation have been proven in boreholes 106/24-1 and 106/24-2 (Figure 20) in the St George's Channel basin, where it consists mainly of mudstones interbedded with subsidiary limestones (or mudstones containing carbonate concretions) and sandstones. At one interval, the beds become sandier and contain more interbedded limestone; anhydrite is interpreted to be present in Borehole 106/24-2 but, based on the sonic and gamma response, may be in error (see Figure 20). The unit is estimated to be 330 m thick in the core of the syncline in the Bristol Channel basin (Evans and Thompson, 1979), where organic-rich shales are prominent.

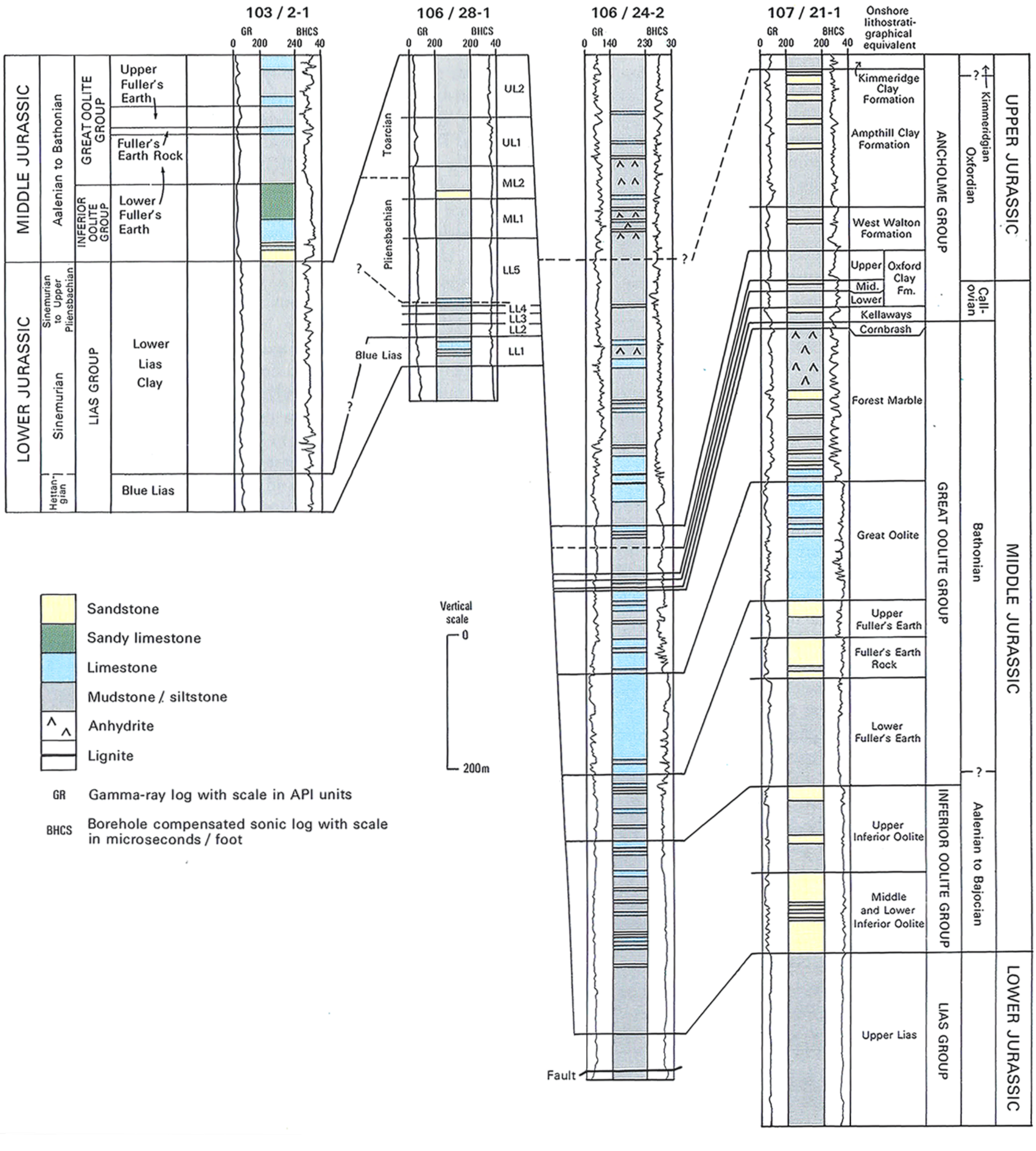


Figure 20 Logs of boreholes in the St George's Channel basin proving Jurassic strata; taken from Tappin et al. (1994), Fig. 34. British Geological Survey © UKRI 2018.

4.2.1.4 Undivided Late Jurassic rocks — LSSR

Rocks of Late Jurassic age do not occur onshore in Wales, but are present offshore in the St George's Channel basin (Figure 20), where they have been proved in five boreholes, and in the Bristol Channel basin. In the former they are underlain by the Great Oolite Group (not a PRTI) and are overlain by undivided

Palaeogene rocks (an LSSR PRTI), whilst in the latter they are believed to be underlain by undivided Mid Jurassic rocks (an LSSR PRTI) and overlain by undivided Early Cretaceous rocks (not a PRTI). In the St George's Channel basin, the unit is bounded to the east by a major fault, and is several hundred metres thick. In the Bristol Channel basin, it occupies the core of an east–west-oriented syncline, is bounded to the north by similarly oriented faults, and is missing its upper part. In both areas, the unit lies largely within the depth range of interest.

The undivided Late Jurassic rocks comprise four units: the West Walton, Ampthill Clay and Kimmeridge Clay formations, and the Portland and Purbeck groups. In the St George's Channel basin, the first two units are dominated by interbedded calcareous mudstone and loose to well-cemented sandstone, with a total thickness of up to 280 m (Borehole 107/21-1); in much of the Bristol Channel basin the equivalent strata are estimated to be up to 520 m thick and consist of fine-grained sandstones and siltstones (Evans and Thompson, 1979), but are absent in Borehole 103/18-1 (Figure 21) in the west, possibly due to faulting. The succeeding Kimmeridge Clay Formation consists mainly of calcareous mudstone. The Portland and Purbeck groups are limited in extent and consist of mudstone with some interbedded, loosely cemented sandstone: in Borehole 103/18-1, in the Bristol Channel basin, it is up to 128 m thick and includes a 26 m-thick limestone.

4.2.1.5 Undivided Kellaways and Oxford Clay formations — LSSR

The Kellaways and Oxford Clay formations do not occur onshore in Wales and are only modelled separately from Mid Jurassic rocks in the St George's Channel basin, where they are underlain by the Great Oolite Group (not a PRTI) and overlain by the Corallian Group and/or Eocene to Miocene rocks (an LSSR PRTI). In the St George's Channel basin, the unit occupies a syncline that plunges south-westwards, increasing its depth of burial in the same direction and locally placing it within the depth range of interest.

The undivided Kellaways and Oxford Clay formations are well known onshore in the UK and can be reliably correlated using geophysical logs (Whittaker, 1985). The gross distribution and structural setting of the unit is only constrained offshore of Wales by shallow cores (see the BGS 1:50 000 geological maps for the Inner Bristol Channel and Severn Estuary, and Bideford and Lundy Island), and deep boreholes penetrating the sequence are relatively scant (Tappin et al., 1994). Nevertheless, they exhibit the characteristic geophysical log motif, allowing accurate correlation and reliable differentiation of constituent facies between the holes.

Offshore, the undivided Kellaways and Oxford Clay formations are dominated by mudstone (Figures 20 and 21) and have a similar expression to the onshore UK succession. A basal silty and calcareous mudstone (Kellaways Clay Member) is overlain by a hard, calcite-cemented sandstone (Kellaways Sand Member), which is itself overlain by a thick sequence of silty to sandy, calcareous mudstones (Oxford Clay Formation). In the western Bristol Channel, in Borehole 103/18-1, the Kellaways Clay Member is 13.5 m thick, the Kellaways Sand Member 8.5 m thick and the Oxford Clay Formation 88 m thick, though the upper part is missing possibly due to faulting (Penn, 1987); further to the east, the Oxford Clay Formation is estimated to be 370 m thick (Evans and Thompson, 1979). In the St George's Channel basin, in Borehole 107/21-1, the Oxford Clay is also up to 88 m thick, but contains three prominent cycles in which the mudstones pass upwards into fine-grained sandstones.

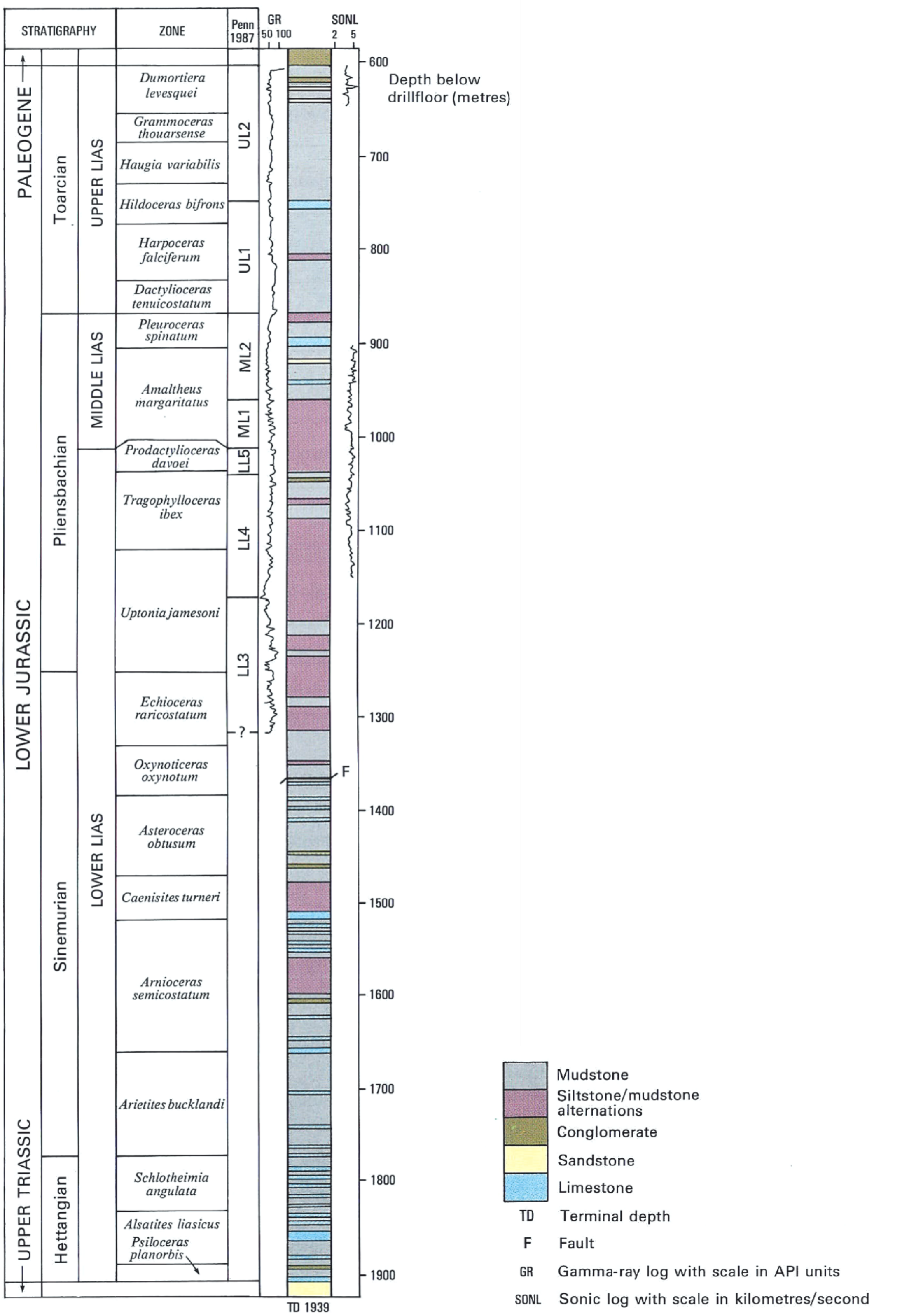


Figure 21 Log of Borehole 103/18-1 from the Bristol Channel basin; taken from Tappin et al. (1994), Fig. 35. British Geological Survey © UKRI 2018.

4.2.1.6 Undivided Mid Jurassic rocks — LSSR

The undivided Mid Jurassic rocks are confined to the Cardigan Bay, St George's Channel and Bristol Channel basins, where they overlie the Lias Group (an LSSR PRTI) and are overlain by Late Jurassic rocks (an LSSR PRTI); locally, they are exposed at the seabed. In both regions, the unit occupies faulted synclines (Tappin et al., 1994) and largely lies within the depth range of interest; the Cardigan Bay Syncline is faulted along its eastern margin and plunges south-westwards, so that the depth of the undivided Mid Jurassic rocks increases in the same direction. The thickness of the unit generally increases towards the centres of the basins: 1165 m were proved in Borehole 107/16-1 where the Cardigan Bay basin abuts the St George’s Channel basin, and approximately 200 m were proved in Borehole 103/18-1 at the western margin of the Bristol Channel basin (Figure 21).

Mid Jurassic strata are not present onshore in Wales, but are well known offshore and onshore elsewhere in the UK (Cope et al., 1980). Here, they are characterised by lateral facies and thickness changes and contain numerous erosion surfaces, making correlation difficult. The successions offshore of Wales are much expanded in comparison, but there nevertheless remains evidence of erosion in the areas of interest along the basin margins including, locally, at the base of the unit (Tappin et al., 1994). The gross distribution and structural setting of the succession is constrained by shallow cores (see the BGS 1:50 000 geological maps for the Inner Bristol Channel and Severn Estuary, and Bideford and Lundy Island) and seismic data, but deep boreholes are relatively scant (Tappin et al., 1994) making it difficult to resolve complex facies and thickness variations.

The undivided Mid Jurassic rocks comprise a lithologically diverse succession and exhibit marked lateral variability, particularly on either side of the Pembroke ridge (Tappin et al., 1994). The unit is composed of three groups: in ascending order, the Inferior Oolite, Great Oolite and Ancholme groups. The first two are not themselves independently considered PRTIs. In contrast, the Ancholme Group, which is equivalent to the undivided Kellaways and Oxford Clay formations, is considered a PRTI.

In the St George’s Channel basin and the western part of the Bristol Channel basin, the Inferior Oolite Group is dominated by sandstone and siltstone respectively; further east in the Bristol Channel basin the unit may be present but is difficult to distinguish within the uniform mudstones that make up the Mid Jurassic rocks in this area (Tappin et al., 1994). The succeeding Great Oolite Group is subdivided onshore into a number of different formations, each of which can be distinguished offshore in the St George’s Channel basin where the limestone-dominated succession is considerably expanded. It includes one mudstone-dominated unit which, in Borehole 107/21-1, is 290 m thick and consists of variably pyritic and calcareous mudstone with thin argillaceous limestones in its lower half; further north, in the Cardigan Bay basin, BGS boreholes 74/22 and 72/38 sampled sandstones and limestone. In the Bristol Channel basin the Great Oolite Group is largely undivided and is dominated by mudstone, locally reaching a thickness of 330 m (perhaps including the Inferior Oolite Group); in the west of the Bristol Channel basin, in Borehole 103/18-1, the unit is represented by 60 m of mudstone and siltstone (Figure 21).

4.2.1.7 Undivided Jurassic rocks — LSSR

The undivided Jurassic rocks are confined to the St George’s Channel and Cardigan Bay basins, including the latter’s onshore expression at Morfa Dyffryn. In both basins, the unit is bounded to the south-east by a major fault. In the St George’s Channel basin, the unit crops out on the seabed, is underlain by the Lias Group (a LSSR PRTI) and, according to the BGS 1:50 000 geological map of Cardigan and Dinas Island, consists entirely of Mid Jurassic strata (a LSSR PRTI). Borehole 107/21-1 proved the Mid Jurassic succession in this area to be up to 1045 m thick (see Figure 20). By contrast, in the Cardigan Bay basin the undivided Jurassic rocks are overlain by Eocene to Miocene strata (an LSSR PRTI) and comprise both Lias Group and Mid Jurassic strata. The Mochras Borehole, which penetrates a nearby part of the Cardigan Bay basin, proved 1305 m of Lias Group strata predominately consisting of interbedded mudstone and siltstone.

Offshore correlation of individual formations within both the Lias Group and the Mid Jurassic is difficult, but the general distribution of the two units, their thicknesses and their structure are constrained from geophysical survey and borehole information (Tappin et al., 1994; BGS 1:50 000 geological map of Cardigan and Dinas Island).

Based on Tappin et al. (1994) and the BGS 1:50 000 geological map of Cardigan and Dinas Island, it seems likely that only the Mid Jurassic component of the undivided Jurassic rocks lies within the depth range of interest.

4.2.1.8 Lias Group — LSSR

The Lias Group occurs onshore and offshore, where it generally overlies the Mercia Mudstone (plus Penarth) Group, but locally rests on Carboniferous strata. Onshore, it comprises thinly interbedded limestone and calcareous mudstone (Howells, 2007), and is confined to the Vale of Glamorgan in South Wales where it lies entirely above the depth range of interest. Offshore, the Lias Group is expanded and is present over an extensive area in the Cardigan Bay, the St George's Channel and the Bristol Channel basins within the depth range of interest; it is absent from the East Irish Sea basin and from the near-coastal parts of the central Irish Sea basin (Jackson et al., 1995). The Mochras Borehole, which penetrates part of the Cardigan Bay basin, proved 1305 m of Lias Group strata predominately consisting of interbedded mudstone and siltstone (Figure 22). In the Cardigan Bay and the St George's Channel basins, the group is bounded to the south-east by major faults, and is mostly overlain by other LSSR PRTIs; locally, it is exposed on the seabed, is absent, or is overlain by the Great Oolite Group of no interest. Seismic reflection evidence suggests that the thickness at Mochras is maintained, or even exceeded, along the axes of these two basins, but diminishes towards their margins (Barr et al., 1981); the Lias Group is 388m thick in Borehole 103/2-1 to the west of Pembrokeshire. In the Bristol Channel basin, the group is repeatedly downthrown to the south by a series of east–west-oriented faults (Tappin et al., 1994), and in the east largely lies above the depth range of interest. A thickness of 494 m was proved in Borehole 103/18-1 at the western extent of the basin, whence it thickens westward to 1075 m in Borehole 102/29-1in the adjacent South Celtic Sea basin, and thins northwards towards Pembrokeshire.

The onshore Lias Group is structurally uncomplicated, gently dipping and particularly boreholes exposed in continuous coastal cliff sections; its full thickness was drilled in a borehole near Bridgend (Wilson et al., 1990). Correlation with the offshore successions is only tentative (Tappin et al., 1994) because the offshore lithostratigraphy is poorly defined, the successions are considerably expanded, there are comparatively few available boreholes, correlation is largely based on downhole geophysical profiles, and the basins are separated and internally faulted and locally disrupted by salt diapirs. Similarly, problems with the interpretation of seismic reflection profiles have led to differences between published interpretations.

The Lias Group consists of mudstone with variable carbonate content, interbedded with argillaceous limestones and, locally, siltstones; an interdigitating marginal facies is present onshore, consisting of conglomerates and oolitic and skeletal limestones (Wilson et al., 1990), but is not observed offshore. Some intervals of mudstone are pyritic and bituminous. The group is subdivided into four units: in ascending order, the Blue Lias Formation, the 'Lower Lias Clay' (now called the Charmouth Mudstone Formation), the 'Middle Lias', and the 'Upper Lias' (now the Whitby Mudstone Formation). Only the Blue Lias Formation is present in the Vale of Glamorgan, where it comprises up to 150 m of thinly interbedded limestone and calcareous mudstone, with individual beds being persistent over distances of at least 10 km (Howells, 2007). The Blue Lias Formation is itself subdivided into four members on the basis of the ratio of limestone to mudstone, but is dominated by the Porthkerry Member (the topmost 120 m) in which the ratio is approximately equal.

Offshore, the Blue Lias Formation is up to 230 m thick and is predominantly comprised of mudstone. It is not well developed at Mochras, but may be represented by the lowest 150 m of mudstone with scant thin limestone interbeds. The Blue Lias passes upwards into the more argillaceous beds of the Lower Lias Clay. It consists of calcareous mudstones that are in part pyritic and organic-rich and which are organised into cycles (up to 15 m thick) that reflect variations in carbonate content. At Mochras it is 746 m thick and includes abundant siltstone in its upper part, whereas in Borehole 106/28-1, to the south-west in the St George's Channel basin, it is 149 m thick and consists of dark grey siltstone and mudstone (see Figure 20).

The Middle Lias contains a higher proportion of siltstone than the rest of the Lias Group. In the Mochras Borehole it is it is 147 m thick and comprises interbedded siltstone and mudstone with some thin limestones. In Borehole 106/28-1, in the St George's Channel basin, it is 110 m thick and consists predominately of siltstone, with thin sandstones at the base. These sediments pass up into 37 m of fine-grained sandstone, which are overlain by mudstone and siltstone of the Upper Lias. In the Mochras Borehole the Upper Lias is 262 m thick; the lower half consists of mudstone with sparse siltstones and limestones, whilst the upper half is interbedded with silty mudstones (Tappin et al., 1994). Further south-west, in the St George's Channel basin, Borehole 107/21-1 penetrated 291 m of calcareous, slightly micaceous mudstones that are assigned to the Upper Lias; even further south-west, 172 m of siltstone were recorded in Borehole 106/28-1. In the Bristol Channel basin, the Upper Lias is about 90 m thick (Evans and Thompson, 1979) and consists of mudstones and silty shales; it increases in thickness to the west, with over 250 m being present in the South Celtic Sea basin (Tappin et al., 1994).

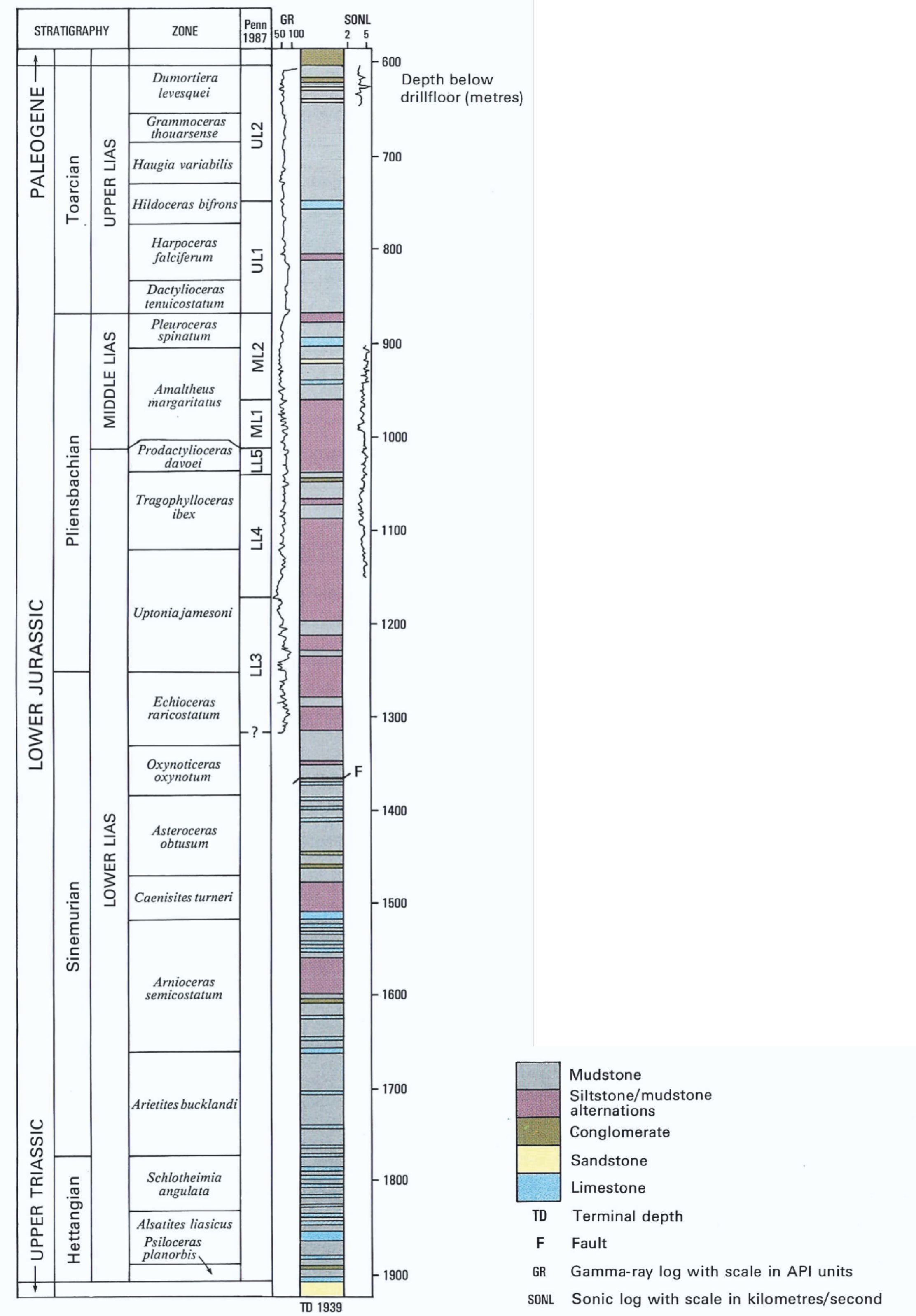


Figure 22 Log of the Lias Group in the Mochras Borehole on the onshore extension of the Cardigan Bay basin; taken from Tappin et al. (1994), Fig. 33. British Geological Survey © UKRI 2018.

4.2.2 Older sedimentary rocks

4.2.2.1 Sidmouth Mudstone Formation — LSSR and EVAP

The Sidmouth Mudstone Formation (a component of the Mercia Mudstone Group) occurs both onshore and offshore. Onshore, it is restricted to a small area between Wrexham and Whitchurch, most of which is within the depth range of interest. Offshore it occurs in the Caernarfon Bay basin (Figure 16) off the north coast of the Llŷn Peninsula, also within the depth range of interest. In both areas, the unit is dominated by mudstone, but includes thick halites (the Northwich Halite and Wilkesley Halite members and the Preesall Halite Member, respectively) within the depth range of interest.

The distribution and thickness of the Sidmouth Mudstone Formation in the Caernarfon Bay basin is poorly constrained, partly due to the scarcity of boreholes and partly because of subsequent erosion; consequently, it is generally shown as part of an undivided Permo-Triassic succession (Jackson et al., 1995). The formation is bounded to the south-east by a major fault that abuts it against late Cambrian metasedimentary rocks (Gwna Group), which are not considered a PRTI, and is variously overlain by superficial deposits (not a PRTI) or Eocene to Miocene Rocks (an LSSR). It is dominated by interbedded silty mudstones and variably dolomitic mudstones with gypsum nodules and veins, but includes thick halites. Borehole 107/01-1 proved 971 m of the formation overlying 64m of sandstone and siltstone below the depth range of interest, which are assigned to the Tarporley Siltstone Formation (the basal component of the Mercia Mudstone Group). One thick halite (the Preesall Halite Member) occurs within the depth range of interest, and two others (the Rossall Halite and Mythop Halite members) were recorded: the Rossall Halite Member is approximately 30 m thick and largely lies below the depth range of interest, whilst the Mythop Halite Member is only approximately 4 m thick. The Preesall Halite Member is 205 m thick and massive with some impurities, including gypsum, calcite or dolomite, and clay and silt; it likely includes subordinate mudstone units up to 30 m thick (Jackson et al., 1995).

The onshore succession is lithologically similar and includes two thick halites, both including subordinate mudstone intervals: the Northwich Halite Member and the higher Wilkesley Halite Member. Borehole Prees 1 proved 181 m of the former and 352 m of the latter, with the proportion of mudstone increasing to >50 per cent in its lower part.

4.2.2.2 UNDIVIDED MERCIA MUDSTONE GROUP AND PENARTH GROUP— LSSR AND EVAP

The Mercia Mudstone Group and overlying Penarth Group are modelled as one unit in NGS3D and both are identified as PRTIs. The Penarth Group overlies the Blue Anchor Formation of the Mercia Mudstone Group and comprises about 12 m of dark grey and grey mudstone with subordinate sandstones, siltstones and limestones, which passes into a more restricted marginal facies. The Mercia Mudstone Group and overlying Penarth Group are described as a combined unit, the Mercia Mudstone Group.

The Mercia Mudstone Group is dominated by mudstone and is restricted to a relatively small area in South Wales between the Vale of Glamorgan and the Severn Bridge where it lies almost exclusively above the depth range of interest. Offshore it is present over an extensive area within the depth range of interest, except to the north of Anglesey and in the East Irish Sea basin, where it is absent or too shallow, and in the Central Irish Sea basin, where it lies below the depth range of interest; these areas are not considered further. Only offshore of north Pembrokeshire are thick units of (unnamed) halite present within the area of interest (Tappin et al., 1994). These are considered to represent the westward-lateral equivalents of the Somerset Halite Member of the adjacent Bristol and Gloucester region. In the Bristol Channel, division of the component halite unit was not possible and the undivided Mercia Mudstone Group is interpreted as an EVAP PRTI.

In the St George’s Channel basin, the Mercia Mudstone Group is bounded to the south-east by major faults, and, in the Bristol Channel basin, it is repeatedly downthrown to the south by a series of east–west-oriented faults. In both basins, it is largely overlain by the Lias Group, another mudstone-dominated LSSR PRTI.

The onshore Mercia Mudstone Group is poorly exposed because it generally occupies a low-lying coastal tract, much of which is covered by superficial deposits. However, it is recorded in abundant boreholes and is well exposed in coastal cliff sections in the vicinity of Barry. Offshore, the unit has been proved by boreholes in all of the basins except for the Central Irish Sea basin and the Cardigan Bay basin (Tappin et al., 1994), although its presence there is indicated on seismic profiles. The base of the group is taken in offshore boreholes at a marked change in gamma ray and sonic log profiles, and the unit may be divided into six geophysical log units, equating to four lithological units. In the Cardigan Bay basin, the presence of the group is strongly implied by evidence from seismic profiles (Dobson and Whittington, 1987).

Up to 160 m of Mercia Mudstone Group are present in the Cardiff–Newport area, where they rest upon a pre-existing, irregular topography comprised of Carboniferous and Devonian strata. The unit is dominated by massive, red-brown dolomitic mudstones and siltstones with common gypsum nodules and veins; these facies locally pass laterally into a 'marginal facies' of interbedded conglomerate, breccia and sandstone. The onshore succession merges with the upper part of the offshore succession and thickens southwards into the adjacent part of the Bristol Channel basin.

Four lithological units are distinguishable offshore of west and South Wales. In ascending order, they are:

1. variably calcareous mudstone with silty interbeds and subordinate sandstone, gypsum and halite
2. halite interbedded with mudstone, dolomite, gypsum and sporadic sandstone
3. silty and variable calcareous mudstones
4. mudstones with subordinate dolomite and gypsum

Unit 4 is only present in the Bristol Channel basin.

In the Bristol Channel basin, the Mercia Mudstone Group thickens from up to 500 m in the east (Brooks et al., 1988) to up to 960 m (Borehole 103/18-1) in the west, mainly due to the greater development of the evaporitic unit 2 below the depth range of interest. Hence, units 3 and 4 dominate the Bristol Channel basin succession within the depth range of interest. In contrast, over 1700 m (Borehole 103/2-1) of the group are present at the southern end of the St George's Channel basin, including thick halites within the depth range of interest (Tappin et al., 1994). Borehole 103/2-1, sited on a salt pillow, penetrated over 800 m of halite: the lower part consists of interbedded halite, anhydrite, mudstone, sandstone and dolomite, whilst the upper part is predominately halite in beds up to 100 m thick (Tappin et al., 1994). In Borehole 106/28-1 there are 750 m of interbedded mudstone and halite, the latter forming beds up to 30 m thick and 30 to 40 per cent in total. Migration of salt into a major fault (the St George's Fault) has created a linear salt wall that is at least 50 km long and up to 3 km wide (Tappin et al., 1994). According to Dimitropoulos and Donato (1983), this was achieved in a highly constrained manner, rather than forming randomly distributed swells and diapirs.

4.2.2.3 Undivided Triassic rocks— LSSR

The undivided Triassic rocks are confined to the Cardigan Bay basin, including its onshore extent in the vicinity of Harlech. They encompass both the Mercia Mudstone Group and overlying strata equivalent to the Penarth Group, and are bounded to the south-east by a major fault. They overlie Carboniferous Coal Measures (not a PRTI) and are overlain by various Jurassic and younger-aged rocks, which are themselves LSSR PRTIs. Only towards the south of their extent do they lie predominately within the depth range of interest.

The undivided Triassic rocks are separately distinguished on the basis of strata encountered at the base of the Mochras Borehole. These were not logged geophysically. The older (i.e. underlying) majority of the unit, presumed to consist largely of the Mercia Mudstone Group, has not been proved in the Cardigan Bay basin, but its presence is strongly implied by evidence from seismic profiles (Dobson and Whittington, 1987) and by its widespread presence in adjacent areas, from which its nature can reasonably be extrapolated.

These Triassic rocks are modelled to be up to 300 m thick. The highest beds, which were sampled at the base of the Mochras Borehole, are equivalent to the Penarth Group but are lithologically distinct (Tappin et al., 1994). They have been divided into two units (Harrison, 1971): a lower one, dominated by carbonate-cemented sandstone with subsidiary breccio-conglomerates, silty limestone and marl, and an upper one, consisting of dolomitised limestone with interbedded carbonate-cemented, fine-grained to pebbly sandstones. These are presumed to overlie the Mercia Mudstone Group (Tappin et al., 1994), which predominately consists of silty and variable calcareous mudstones, locally including a thick unit of halite. Only the Mercia Mudstone Group component of the undivided Triassic rocks is a PRTI.

4.2.2.4 Cumbrian Coast Group — LSSR

The late Permian Cumbrian Coast Group occurs in the Central Irish Sea and East Irish Sea basins off the north coast of Wales, and onshore in a small area in the Vale of Clwyd. However, it only lies within the depth range of interest in the East Irish Sea basin, where it is confined above (Sherwood Sandstone Group) and below (older Permian strata) by rock types that are not PRTIs. Regional data indicate that the Cumbrian Coast Group thickens northwards away from the north coast of Wales, probably in a rim that is broadly parallel to it (Jackson et al., 1995). It consists of interfingered evaporites, mudstones and sandstones that are locally organised into up to four cycles (BS1–4 of Jackson et al., 1987); these cycles are more speculative in the vicinity of North Wales, where the unit may contain localised marginal breccias and a greater proportion of sandstone.

The nature and thickness of the Cumbrian Coast Group off the north coast of Wales is poorly constrained. Regional seismic data and a limited number of boreholes are available (see the BGS 1:250 000 geological maps for Liverpool Bay and Anglesey), but dating and internal correlation of the late Permian sequence is tentative: towards the margins of the East Irish Sea basin there is a lack of fossils and an absence of marker beds, and the cyclical pattern of sedimentation seen within more basinal settings to the north breaks down (Jackson et al., 1995).

Based on regional understanding, the Cumbria Coast Group only includes cycles BS1 and BS2 within the area of interest, and substantial halite deposits are probably not be present (Jackson et al., 1995); the group is therefore not considered to contain an EVAP PRTI. Deposits of the first (i.e. lowest) cycle, BS1, consist of calcareous siltstone overlain by fine-grained dolomite and are consistently around 26m thick. Cycle BS2 consists predominately of mudstone, locally with a thin (generally <2 m thick) sandy limestone at its base and with variable amounts of sandstone higher up (Jackson et al., 1995). Although its thickness and character in the area of interest is largely uncertain, the Cumbrian Coast Group is tentatively retained as a LSSR PRTI.

4.2.2.5 Warwickshire Group (siltstone and sandstone) — LSSR

Siltstone and sandstone-dominated Warwickshire Group rocks are confined to North Wales in the Vale of Clwyd and to the south-west of Wrexham. In these areas, Warwickshire Group rocks largely lie within the depth range of interest, but are overlain and underlain respectively by Permian and Carboniferous rocks that are not PRTIs; the unit is faulted against other rocks that are not PRTIs along the eastern side of the Vale of Clwyd. To the south-west of Wrexham, the unit includes an intervening division of the Warwickshire Group comprising mudstone, siltstone, sandstone, coal, ironstone and ferricrete (see Warwickshire Group (mudstone)).

The distribution of concealed Warwickshire Group rocks is conjectured from surface outcrop and from a limited number of boreholes (see Warren at al., 1984). In the Vale of Clwyd, these include Foryd [SH97NE/2], Frondyffryn [SJ06NE/6], St Asaph [SJ07SW/14] and Pont Ystrad [SJ06SE/1]; south-west of Wrexham the most important borehole is Erbistock 1 [SJ34SW/35]. The unit is poorly exposed in the Vale of Clwyd, and the boreholes are mostly shallow, hence its subcrop is very poorly constrained. Detailed geophysical gravity and seismic refraction traverses exist for parts of the vale (Warren et al., 1984). These support the presence of the mapped faults and suggest that the Warwickshire Group may be up to 300 m thick in the southern part of the vale.

The group comprises interbedded, metre-scale mudstones, locally calcareous or silty, with subordinate (often micaceous and flaggy) metre-scale sandstones and seatearths, arranged into intervals up to 25 m thick, separated by metre to decametre-scale sandstone intervals. The St Asaph Borehole proved about 90 m, including a 15 cm-thick poor coal, whilst the Frondyffryn Borehole proved 42 m, containing a high proportion of seatearth and a 30 cm limestone. The unit is only tentatively retained as an LSSR PRTI.

4.2.2.6 Warwickshire Group (mudstone) — LSSR

Warwickshire Group (mudstone) rocks are largely confined to South Wales, where they occupy the core of a major east–west-oriented syncline whose axis passes through Llanelli (see Howells, 2007, Fig. 31). Much of the unit lies within the depth range of interest along the axis of the syncline, particularly in the vicinity of Swansea and to the north of Cardiff, but it is too shallow along the syncline’s northern and southern limbs and in the vicinity of Rhondda.

A fault-bounded inlier of Warwickshire Group mudstone is present in Pembrokeshire. Here, at least the lower part of the unit lies within the depth range of interest, but the inlier is only small and bounded to the north by rock types that are not PRTIs; to the south it is faulted against HSRs. Warwickshire Group (mudstone) rocks overlie older Carboniferous strata that are not PRTIs in all areas. This setting may limit the unit’s potential as a PRTI.

Within the South Wales Syncline, Warwickshire Group mudstone rocks are not concealed beneath younger strata and they crop out widely, though they are locally obscured by superficial deposits, particularly in valleys. Hence, the unit’s distribution, character and structure are very well constrained. The depth to the base of the unit is conjectured from a combination of surface outcrop, abundant boreholes, coal mining activity, and a limited amount of seismic reflection data (see Chadwick and Evans, 2005). Correlation between locations is possible across the whole area by means of laterally persistent, named coal beds. The unit is well documented in Strahan et al. (1907); Woodland and Evans (1964); Downing and Squirrell (1965); Squirrell and Downing (1964; 1969), and Barclay (1989; 2011), and a regional summary is given in Waters et al. (2009).

The mudstone-dominated Warwickshire Group comprises three divisions: in ascending order, the Deri Formation, limited to the eastern part of the syncline; the Pennant Sandstone Formation, subdivided by coal seams into five units, and the Grovesend Formation. The Deri Formation comprises up to 180 m of mudstones, seatearths and sandstones with subsidiary siltstones and conglomerates, and is not present west of Pontypridd. The overlying Pennant Sandstones Formation is up to 1335 m and is dominated by feldspathic and micaceous sandstones with thin mudstone/siltstone and seatearth interbeds, commonly arranged into fining-upward sequences each several metres thick. It is thickest in the vicinity of Swansea and thins both to the north and east; in the eastern part of the syncline it is reduced to approximately 275 m. The Grovesend Formation is up to 426 m thick and predominately consists of mudstones and siltstones with well-developed coals and subordinate, though locally thick, sandstones. Only this latter, uppermost division of the Warwickshire Group has the requisite thickness and lithological characteristics to be considered a PRTI. However, the Grovesend Formation is discounted in this area on the basis of two considerations:

- it is isolated in relatively small areas in the cores of synclines and fault troughs between Llanelli and Neath in the west, and in the vicinity of Llanhilleth and Caerphilly in the east (Thomas, 1974)
- only in two small areas (each less than 2.5 km^2) in the west does any part of the formation lie within the depth range of interest

4.2.2.7 UNDIVIDED EARLY DEVONIAN ROCKS — HSR

The undivided Early Devonian rocks crop out only in a narrow band inland of Dulas Bay on Anglesey. However, small, concealed masses are modelled south of the Variscan cleavage front (Figure 26) in south Pembrokeshire, offshore of St Govan’s Head, and on the Gower, but each is structurally isolated from other HSRs and the last lies entirely below the depth range of interest, therefore, the unit is only considered a PRTI where it occurs on Anglesey.

On Anglesey the unit forms part of the local (presumed) Lower Old Red Sandstone succession and, at least locally, is cleaved and structurally complex. Only a 130 m-thick interval in the lower part of the unit, equivalent to the Traeth Bach Formation, is mudstone-dominated: the rest is highly heterolithic and includes abundant metre to decametre-scale sandstone beds (Barclay et al., 2005). The formation is dominated by calcrete-rich, muddy siltstones, with minor thin conglomerates and sandstones. The calcrete is mainly in the form of nodules, but massive, metre-scale dolomite limestones occur at several levels.

Within the depth range of interest the unit largely overlies late Cambrian rocks (an HSR) and is faulted against them in the south.

4.2.3 Basement rocks

4.2.3.1 UNDIVIDED LUDLOW ROCKS — HSR

Undivided Ludlow rocks crop out over an extensive area along the eastern margin of Wales, largely outside of the Acadian cleavage front. However, locally cleaved anchizone, or higher, metamorphic grade (Figure 10) mudstone-dominated successions, (Warren et al., 1984), are present over an extensive area in north-east Wales in the vicinity of Colwyn Bay, Denbigh and Llangollen, and locally occur within the depth range of interest and represent a PRTI.

Within the area of interest, the unit is essentially equivalent to the Elwy Formation (the ‘Elwy Group’ of Warren et al., 1984). It is up to 1750 m thick south of Colwyn Bay, generally thinning to the east (450 m in the Clwydian Range) and the south-east (610 m in the vicinity of Llangollen). Two facies dominate: striped silty mudstones, and disturbed beds. Only locally do sandstones form a significant proportion of the unit, with the thickest interval reaching 55 m. The striped, silty mudstones consist of alternations of turbiditic, silty mudstone and more or less calcareous siltstone or fine sandstone, generally on a centimetre scale, and include thin bands of laminated, hemipelagic mudstone. The disturbed beds consist of massive, wholly destratified or partly contorted intervals ranging from highly fractured, slightly silty mudstone to muddy sandstones, and they range up to 450 m thick. They are subject to rapid lateral variation in lithology, possess an irregular cleavage, are comparatively heavily faulted, and notably resistant to mechanical removal.

Lateral facies changes and thickness variation are numerous and significant within the unit but, at least in the Colwyn Bay and Denbigh regions (Warren et al., 1984), it exhibits a general three-fold division. The basal division (approximately 400 m thick) consists predominately of disturbed beds; the middle division (275 to 670 m thick) comprises an alternation of striped mudstones and disturbed beds (locally up to 75per cent), and sandstones are comparatively numerous (up to 10 per cent of the succession), and the upper division comprises striped, silty mudstones with relatively few disturbed beds. Local variations are apparent. Disturbed beds are absent in the basal division in the Clwydian Range, and sandstones increase in importance at this level towards the north and east; sandstones are virtually absent in the middle division south-east of Nantglyn, although many of the disturbed beds here are sandy, and laminated hemipelagic mudstone comprises a greater proportion of the striped, silty mudstone facies of the upper division towards the south-east.

The mudstone-dominated Ludlow succession locally lies within the depth range of interest in the Colwyn Bay and Denbigh regions, and overlies (and is locally faulted against) mudstone-dominated Wenlock rocks, an HSR. In the Vale of Clwyd, it is overlain by Carboniferous rocks, which are not of interest, and on the eastern side the unit lies below the depth range of interest. In the Clwydian Range the unit is underlain by undivided early Palaeozoic rocks, an HSR, and along its western margin it is faulted against rocks that are either not of interest or are a potential LSSR (Warwickshire Group).

4.2.3.2 UNDIVIDED WENLOCK ROCKS — HSR

Undivided Wenlock rocks crop out over an extensive area along the eastern margin of Wales, mostly outside of the Acadian cleavage front. However, anchizone, or higher, metamorphic grade (Figure 23), locally cleaved, mudstone-dominated successions (Warren et al., 1984) are present over an extensive area in north-east Wales in the vicinity of Colwyn Bay and Denbigh within the depth range of interest and represent a PRTI; small areas also occur to the north of Newtown and east of Mallwyd.

The undivided Wenlock rocks comprise a series of mudstone-dominated units with a thick (up to 1750 m) sandstone-rich unit (not a PRTI) near or at the base corresponding to the Denbigh Grits Group or Penstrowed Grits Formation. The mudstone-dominated succession, mostly equivalent to the Nantglyn Flags Formation, may be up to 800 m thick and comprises four main facies: ribbon-banded mudstones; striped, silty mudstones; mottled mudstones, and disturbed beds (Warren et al., 1984; Wilson et al., in press). The ribbon-banded mudstones dominate and consist of regular alternations of thin bands (averaging 20 mm) of turbiditic, silty mudstone and hemipelagic, laminated mudstone; the striped, silty mudstones consist of centimetre-scale alternations of turbiditic, silty mudstone and more or less calcareous siltstone or fine sandstone (see undivided Ludlow rocks); the mottled mudstones consist of irregularly cleaved, calcareous, silty mudstone, and the disturbed beds consist of massive, wholly destratified or partly contorted examples of the other facies (see undivided Ludlow rocks). Individual disturbed units and mottled mudstone beds persist over tens of kilometres and may be up to 350 m and 76 m thick respectively, though they exhibit marked lateral variation (Warren et al., 1984). Near Mallwyd and Newtown, up to 150 m of ribbon-banded mudstones (equivalent to the Nant-Ysgollon Mudstone Formation) lie below the sandstone-rich unit and define the base of the Wenlock: they thicken towards the north-west where they contain increasingly abundant thin beds and laminae of turbiditic sandstone and siltstone (Wilson et al., 2016).

Near Mallwyd and Newtown, the mudstone-dominated Wenlock succession overlies either undivided, mudstone-dominated Llandovery rocks (a PRTI) or sandstone-dominated Llandovery rocks (not a PRTI). However, only to the north of Newtown do modest areas of the unit occur within the depth range of interest. In the Colwyn Bay and Denbigh areas, the mudstone-dominated Wenlock succession mostly overlies the Denbigh Grits Group, which is not a PRTI; locally, in the south near Llangollen, it overlies undivided, mudstone-dominated Llandovery rocks (a PRTI) whereas in the Clwydian Ranges it overlies undivided early Palaeozoic rocks (also a PRTI) but at least locally including the Denbigh Grits Group (not a PRTI). Faults along the western and eastern margins of the Clwydian Range mostly abut the mudstone-dominated Wenlock succession against Carboniferous limestone units, which are not PRTIs; the succession lies below the depth range of interest in the Vale of Clwyd. Almost everywhere, it is overlain by undivided Ludlow rocks, which are a PRTI.

4.2.3.3 UNDIVIDED LLANDOVERY ROCKS — HSR

Undivided Llandovery rocks crop out over an extensive area of Mid Wales to the south of Mallwyd, and much of the unit lies within the depth range of interest.

These rocks comprise a series of mudstone-dominated units, representing HSRs where they preserve a slaty cleavage in the west of Wales (i.e. are of anchizone, or higher, metamorphic grade (Figure 10)), separated by thick packages of rhythmically interbedded sandstone and mudstone. The latter were sourced from the south and their spatial distribution is (in part) controlled by irregularities that were present in the sea floor at the time of deposition. Hence, they locally exhibit rapid lateral changes in facies and thickness (Davies et al., 1997), causing considerable variability in the total thickness of the Llandovery rocks, which reaches a maximum of approximately 3000 m. Despite this spatial complexity, many individual mudstone-dominated units can be recognised across the whole region.

Typically, individual mudstone-dominated units are several hundred metres thick and comprise thinly bedded mudstone, with only scattered thin beds of siltstone and fine-grained sandstone. At several intervals, this facies passes upwards and laterally into similar (or greater) thicknesses of rhythmically interbedded sandstone and mudstone; sandstones may form up to 50 per cent of this facies and generally form beds <0.1m thick, ranging up to 1.5 m thick (Figure 23). Towards the top of the Llandovery rocks, this facies may also include abundant, thin to thick-bedded (up to 2 m thick), clay-rich sandstones that are sometimes amalgamated into packages up to 6m thick. Locally, as for example in the Llanilar district (BGS 1:50 000 geological map of Llanilar and Rhayader; Davies et al., 1997), sandstone-rich facies may dominate the Llandovery rocks; in the east, in the vicinity of Llanwrtyd Wells, massive destratified mudstones become more important and the lower half of the succession includes several channelised bodies (up to 15 m thick) of conglomerate.

4.2.3.4 Undivided Ashgill rocks — HSR

Undivided Ashgill rocks crop out extensively in Wales, particularly in an arc extending eastwards from Cardigan to near Llandovery and thence northwards towards Llanbister, at Plynlimon, and along the southern and eastern margins of Snowdonia National Park; other substantial areas occur to the south of Machynlleth and on the Llŷn Peninsula. The area between Llandovery and Llanbister, in particular, is heavily faulted. Much of the unit lies within the depth range of interest, particularly in the vicinity and to the south-east of Cardigan, around Plynlimon, and east of Snowdonia National Park; the majority of the unit on the Llŷn Peninsula lies above the depth range of interest.

The undivided Ashgill rocks are dominated by mudstone, some of which is silty or interbedded with subsidiary siltstones and sandstones. South of a line between Aberystwyth and Newtown they have a total thickness of up to approximately 2000 m; further north they generally reduce in thickness so that along the southern edge of Snowdonia only approximately 600 m are present. South of Aberystwyth and Newtown, the unit has a constant character and consists of 2 parts. Its lower part (up to 1500 m) comprises well-cleaved mudstones with thin (generally <1 cm thick), sparse beds of fine-grained sandstone that may locally increase to approximately 20–30 per cent of the unit (Davies et al., 2003); its upper part (up to 1200 m) comprises silty and silt-laminated mudstone, locally interbedded with sandstones that are individually 1–2 m thick and occur in packets that may exceed 10 m in thickness (Wilby et al., 2007). Thick-bedded, coarse-grained units, each up to 300 m thick, interfinger with the mudstones towards the eastern margin of the area of interest (Schofield et al., 2004a), and massive units of mudstone comprise an increasingly greater proportion of the upper part here too.

The undivided Ashgill rocks exhibit greater variability north of a line between Aberystwyth and Newtown (see Cave and Hains, 1986) and, immediately to the north, generally have a higher proportion of sandstone. Here, the basal few hundred metres consist of varying proportions of thinly interbedded mudstones, siltstones and sandstones, or variably sandy mudstone and siltstone. This is succeeded by up to 400 m of rather massive, poorly cleaved, sandy mudstone with interbedded sandstones (each up to 10 m thick), with up to 180 m of clayey sandstone and subordinate mudstone at the top, and then up to 250 m of massive, poorly cleaved mudstone.

Further north, along the southern edge of Snowdonia National Park, the Ashgill rocks are dominated in the lower part by well-cleaved, silty mudstone with units (up to 20 m thick) of laminated mudstone, and in the upper part by massive, poorly cleaved, silty mudstone, with scant, decimetre-scale, coarse-grained units.

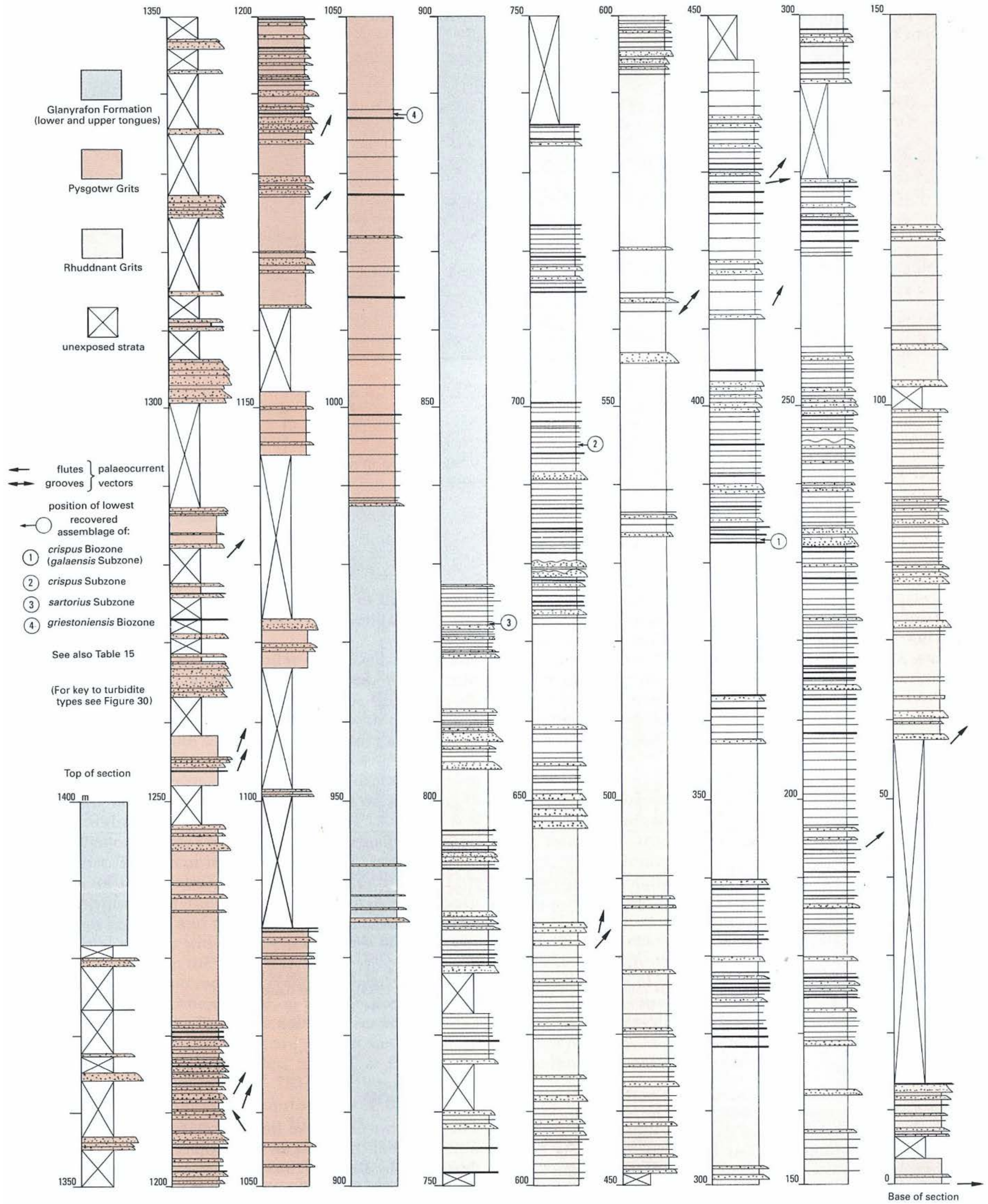


Figure 23 Representative composite graphic log of part of the undivided Llandovery rocks succession in the Llanilar and Rhayader district; taken from Davies et al. (1997), Fig. 31. British Geological Survey © UKRI 2018.

4.2.3.5 UNDIVIDED CARADOC ROCKS — HSR

Undivided Caradoc rocks crop out extensively around the periphery of Snowdonia National Park and on the Berwyn Mountains; smaller areas occur at Cardigan and Llanwrtyd Wells. The latter, in particular, is heavily faulted. To the north-west of Carmarthen, in the Berwyn Mountains and in the vicinity of Snowdonia National Park, these rocks lie largely within the depth range of interest.

These rocks vary considerably across Wales in terms of facies and thickness, and locally include significant volcanic intervals. The unit is intensely faulted in the area between Cardigan and Carmarthen, and some of these structures influenced deposition, resulting in dramatic facies changes across them (Davies et al., 2003). In the vicinity of Cardigan, the unit comprises up to 1000 m of finely cleaved mudstone with subsidiary laminae and thin beds of siltstone and sandstone; north of a major fault, the upper part is replaced by at least 1200 m of thin to thick-bedded sandstone interbedded with mudstone. Further south, towards Carmarthen, the Caradoc rocks are represented by the Drefach Group and comprise approximately 300 m of laminated, locally calcareous mudstone.

Further north-east, in the vicinity of Llandrindod Wells, the undivided Caradoc rocks are dominated by mudstone (at least 600 m thick), which is variably sandy and poorly bedded in its lower part, and finely cleaved above. Even further north, in the Berwyn Mountains, the lowest 1500 m comprise mudstones with scattered beds of tuff, and the succeeding 1100 m is composed principally of medium-bedded (generally <1 m) siltstone and fine-grained sandstone, with subordinate, interbedded, sandy mudstone.

The succession surrounding Snowdonia National Park exhibits substantial lateral facies variations, but is dominated by a thick sequence of monotonous, generally well-cleaved silty mudstones with a few sandstone-rich intervals, overlain by thin to thick-bedded siltstones and sandstones with subordinate silty mudstones; both units are several hundred metres thick and, together, locally total over 1500 m. These are interbedded with (and confined by) substantial volcanic units, themselves HSR PRTIs.

4.2.3.6 UNDIVIDED LLANVIRN ROCKS — HSR

Undivided Llanvirn rocks crop out extensively in North Wales on the Llŷn Peninsula and in the northern part of Snowdonia National Park, as well as in a narrow, faulted tract between Fishguard and Carmarthen in Pembrokeshire. The unit is also present at depth across a wide area to the north of Newtown, but lies entirely below the depth range of interest. Part, or all, of the unit lies within the depth range of interest across much of North Wales, where, except locally, it forms part of a thicker succession of HSRs. In Pembrokeshire, it intermittently lies within the depth range of interest and is underlain and overlain by other HSRs, but to the north and east of Cardigan it dips below the depth range of interest. Across all of Wales, the unit passes laterally into, and is interleaved with, thick volcanic successions (Howells and Smith, 1997); these are the Ordovician volcanic rocks and sills HSR.

The character of the Llanvirn rocks in the Fishguard and Carmarthen districts varies across a broad fault zone that defines the southern limit of the area of interest (Wilby et al., 2007; Burt et al., 2012). To the north of the fault zone, the unit comprises up to 1300 m of relatively monotonous, pyritic, cleaved mudstone with scattered sandstones and felsic tuffs, each up to 10 m thick. However, within the fault zone, and to the south, the succession is thinner (up to 400 m), more silty, better cleaved, and the sandstones are thinner (<20 cm thick) and less abundant.

In the northern part of Snowdonia National Park, the unit comprises finely laminated and well-cleaved, micaceous mudstones and silty mudstones with thin siltstone beds and laminae that increase progressively upwards. It is up to 700 m thick but, locally, is much reduced or even cut out by an unconformity (Howells and Smith, 1997). Impersistent basic and acidic tuffs are scattered throughout and, to the south-west of Cadair Idris, the unit additionally includes sandstones and muddy conglomerates, each 1–3 m thick (Pratt et al., 1995).

On the Llŷn Peninsula, a basal unit (up to 90 m thick) is locally present beneath the monotonous mudstones (up to 600 m thick). It is dominated by thinly bedded (0.5–2.0 cm thick) sandstones, ferruginous siltstones and ironstones, and locally contains basaltic lava and acidic tuff (Young et al., 2002).

4.2.3.7 UNDIVIDED ARENIG ROCKS — HSR

Undivided Arenig rocks crop out extensively in south-west Wales (including offshore of Cardigan) and across smaller areas on the Llŷn Peninsula and around the periphery of Snowdonia National Park. In south-west Wales, in particular, they are heavily faulted, and elsewhere they are commonly steeply dipping. The unit is present within the depth range of interest to north-west of Carmarthen, to the south-east of Fishguard, on the Llŷn Peninsula, and in central Snowdonia.

The rocks in south-west Wales and North Wales differ from one another, but in both areas they rest unconformably on a range of strata, including undivided Tremadoc rocks and undivided late Cambrian rocks, which are HSRs. In south-west Wales, the unit is bounded to the north and south by major faults and is dominated by a monotonous sequence of well-cleaved mudstones and silty mudstones, up to 1200 m thick; at its base is a thinly interbedded sandstone and silty mudstone sequence (up to 300 m).

In contrast, in North Wales, the unit is dominated by sandstone, up to 600 m thick. It includes a variety of thin to thick-bedded, pebbly, flaggy, and volcaniclastic rocks. These exhibit considerable lateral variations in thickness, particularly across certain faults, and the whole unit may be cut out beneath an overlying unconformity.

Hence, only the Arenig rocks in south-west Wales are considered PRTI.

4.2.3.8 Undivided Tremadoc rocks — HSR

Undivided Tremadoc rocks only crop out in a narrow band around the periphery of the southern part of Snowdonia National Park; in south-west Wales and the Llŷn Peninsula they are present at depth almost entirely below the depth range of interest.

The Tremadoc rocks fringing Snowdonia National Park thicken eastwards and northwards (where they reach up to 900 m) and comprise monotonous, well-cleaved mudstone with intervening sandstone-dominated units. The latter increase in abundance in the north, are laterally persistent over several kilometres, and the two most important ones are more than 100 m thick. Locally, for example in the north-east crop, the rocks are reduced or entirely cut out by an overlying unconformity.

4.2.3.9 Ordovician to Silurian unnamed igneous intrusions, felsic rock — HSR

Abundant, principally Ordovician, felsic intrusions (granite, rhyolite, microtonalites and allied rocks) crop out on the Llŷn Peninsula and in Snowdonia National Park. They are intruded into the Cambrian and Ordovician succession, much of which is itself an HSR, and frequently occur within the depth range of interest. Many of the intrusions, such as those on the Llŷn Peninsula, are discordant, pluton-like bodies, whereas others, such as those on Cadair Idris, are relatively concordant, laccolith-like bodies. They vary considerably in size: many are relatively small and form isolated bodies; others, such as the granites, are likely to be more extensive at depth, despite having only relatively small surface expressions (typically only a few square kilometres). Several small bodies also occur in north Pembrokeshire on Dinas Island and St David’s Head, but are excluded as PRTIs because they are limited to narrow, fault-bounded tracts.

Although the granites in the Llŷn cluster are isolated at surface by a series of north-east-trending faults, it is envisaged that they merge at depth within the confines of the fault system (BGS 1:50 000 geological map of Nefyn and part of Caernarfon). Elsewhere, the size of any associated metamorphic aureole may provide an indication of the extent and depth of an intrusion below the surface, and relationships to bedding at surface can be extrapolated below ground. For example, the granite immediately to the north-west of Ffestiniog is estimated to form a steep-sided, subvertical body that extends some 10km to the north-east and 5 km to the south-west of its 4 km^2 outcrop, based on the extent of its hornfels zone and associated gravity and magnetic anomalies (Howells and Smith, 1997). Similarly, the intrusive microtonalite complex at Nant Braich y Ceunant all lies within two Cambrian formations and probably forms an interconnected series at depth, extending northwards as a series of fingers (Figure 24).

The granites and microtonalites in North Wales are generally homogeneous, poorly jointed and fine-grained, with locally intense sericitic alteration, and may include pegmatitic marginal facies. Besides large-scale doming, the strata immediately overlying some intrusions are folded and hornfelsing generally extends only tens of metres away; brecciation is uncommon. The microgranite laccolith at Cadair Idris is typical of many others in the region: it is up to 600 m thick and exhibits both discordant and concordant relationships with the country rock. The rhyolite intrusions in North Wales are mostly quite small, are frequently associated with broadly coeval volcanic successions, and have a complex distribution pattern. They are typically massive, columnar jointed, flow-banded and autobrecciated, with a devitrified groundmass (Howells and Smith, 1997).

4.2.3.10 Ordovician to Silurian unnamed igneous intrusions, mafic rock — HSR

Mafic igneous rocks occur as isolated intrusions in Snowdonia National Park, at the western tip of the Llŷn Peninsula, and in north Pembrokeshire. They are dominated by partially transgressive dolerite sills, but include discordant bodies too, and are largely confined to Cambrian and Ordovician strata, most of which are HSRs themselves. In most areas, the intrusions are only likely to comprise a relatively minor component of the total rock mass within the depth range of interest. Mafic intrusions also occur in the Builth and Shelve inliers, but are not considered PRTIs because they are hosted by units that lie outside of the Acadian cleavage front (Figure 15).

In Snowdonia National Park the mafic igneous intrusions (locally not divided from intermediate intrusions) are confined to late Cambrian to Llanvirn strata in the south, and Llanvirn to Caradoc strata in the north, often in association with Ordovician volcanic rocks and sills (also an HSR); they are largely absent from sandstone-dominated parts of the successions (Allen and Jackson, 1985) and are generally absent from the central and western regions of the Harlech dome. Typically, they are massive, medium grained and well jointed, with only narrow (a few centimetres wide) chilled margins and hornfelsed zones (rarely more than a few metres wide); the largest sills are up to 350 m thick (Pratt et al., 1995). Locally, they may contain rafts of country rock up to 70 m long and 10–15 m thick.

At least two mafic sills at the western tip of the Llŷn Peninsula are over 100 m thick (Gibbons and McCarroll, 1993). They are hosted by Llanvirn rocks, an HSR, whose western margin abuts Proterozoic crystalline basement, another HSR, across a major shear zone.

In Pembrokeshire, the mafic igneous rocks are largely confined to a 2 km interval of Llanvirn strata (an HSR) along the northern margin of the Preseli Hills. These are overlain by Ordovician volcanic rocks and sills (an HSR) and together they dip north until they are displaced below the depth range of interest by a major fault in the vicinity of Newport (Burt et al., 2012).

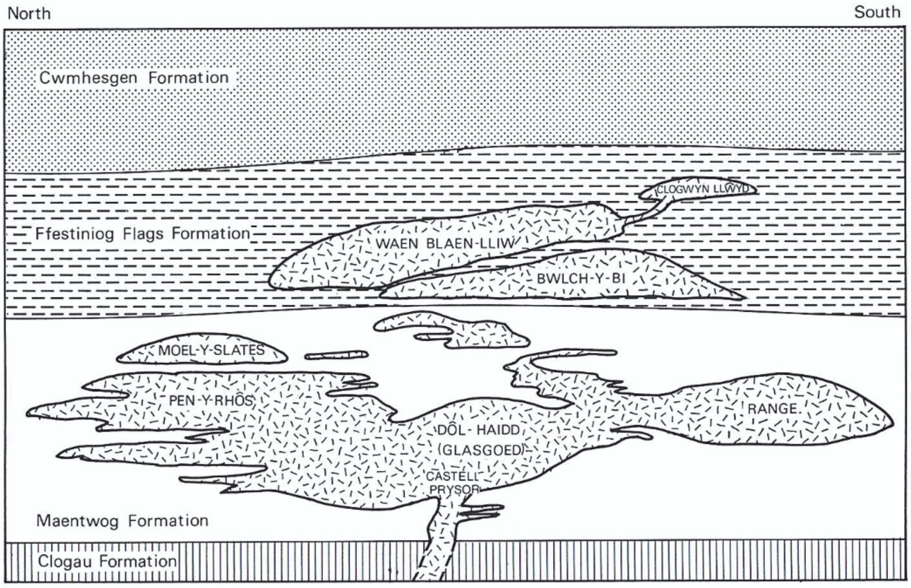


Figure 24 Schematic representation of a north–south section through the unnamed granite intrusion complex at Braich y Ceunant prior to folding; taken from Allen and Jackson, 1985, Fig. 15. British Geological Survey © UKRI 2018.

4.2.3.11 Undivided Ordovician volcanic rocks and sills — HSR

Ordovician volcanic rocks and sills occur on the Llŷn Peninsula, in Snowdonia National Park and in north Pembrokeshire; beyond the area of interest they also occur to the north-east of Newtown and in the vicinity of Builth Wells. Each area corresponds to a discrete volcanic centre (or centres), and the unit is largely confined to the immediate vicinity of these. The unit typically wedges out away from each centre and passes laterally and vertically into background sediment (Howells and Smith, 1997); locally, the centres are defined by faults and certain intervals of the unit may be confined by these structures or ponded within them (see Howells and Smith, 1997).

In Pembrokeshire, the unit occupies a series of narrow, faulted inliers, as well as a more extensive tract that extends inland from Fishguard to Crymych. Within that tract, the unit dips to the north, where it is bounded by a fault that displaces the unit below the depth range of interest. In North Wales, the unit occurs at multiple horizons and crops out in a series of folds (Howells and Smith, 1997). In general, the unit dips away in all directions from the Snowdonia massif, and rarely lies within the depth range of interest over extended distances; locally, as on the Llŷn Peninsula in the core of a north-east to south-west oriented-syncline, it does lie within the depth range of interest over an extended distance. Almost everywhere, the unit is confined by other HSRs.

The following account draws on brief descriptions of the unit given by Howells et al. (1985), Schofield et al. (2004b) and Burt et al. (2012), and in detail in Pratt et al. (1995), Howells and Smith (1997) and Young et al. (2002); a summary of the constituent lithostratigraphical units (including their lithology and thickness) and their relationships to one another is given by Rushton and Howells (1998).

The undivided Ordovician volcanic rocks and sills are a heterolithic mix of acidic, high-level intrusions, lavas and pyroclastic rocks, including breccias, tuffs and tuffites, with subordinate basic igneous components. They exhibit marked lateral variations in thickness and lithology, and are intercalated in a complex manner with silty mudstones and subordinate tuffaceous sandstones, locally comprising intervals that are several tens of metres thick. Rhyolites are locally important, but their relationships (intrusive versus extrusive) are often difficult to determine, and the tuffs vary from being welded and flow banded to graded and crystal rich. Individual, coherent packages (equating to formations) are typically 100 m or more thick, and most beds are approximately 10 m or less thick.

Maximum thickness varies considerably according to location and horizon but, locally, the unit may be more than a kilometre thick, as in the Goodwick area (Burt et al., 2012). Locally, it may be reduced or cut out beneath intra-Ordovician unconformities.

4.2.3.12 Ordovician felsic lava — HSR

This unit only crops out along a relatively short (approximately 10 km long) and narrow (1 km wide) tract to the south-west of Conwy, and corresponds to the Conwy Rhyolite Formation (Howells et al., 1985). Across much of its extent, it is overlain and underlain by other Ordovician HSRs and, at its southern extent, it abuts and interdigitates with more mafic lavas and intrusions (Howells, 2007). However, locally it has a faulted lower contact with these strata.

The unit is composed of thick rhyolite lavas and interflow breccias with subsidiary intercalated acidic tuffs and siltstones, the latter becoming more common southwards. It thickens northwards, reaching a maximum of 800 m. Near Conwy, the unit is intruded by a related rhyolite volcanic plug (Howells et al. 1985). Its relatively restricted distribution may limit its utility as a PRTI.

4.2.3.13 Undivided Ordovician rocks — HSR

The undivided Ordovician rocks only crop out on Anglesey; elsewhere they are concealed beneath younger strata and, except for in the vicinity of Llandovery, they largely lie below the depth range of interest. In the vicinity of Llandovery, the unit refers to Caradoc and older Ordovician strata and is overlain by undivided Ashgill rocks, themselves an HSR. On Anglesey, the unit coincides with Arenig to Caradoc-aged strata and, locally, is interpreted to be partly concealed beneath over-thrust sheets of late Cambrian rocks (also an HSR).

These rocks comprise a mix of mudstone- and sandstone-dominated units. In the vicinity of Llandovery, they are represented by a lower, well-cleaved, monotonous mudstone (at least 600 m thick); a middle, thinly interbedded sandstone, siltstone and limestone unit (up to 700 m thick); and an upper fissile and locally calcareous mudstone (up to 300 m thick) with a few decimetre-scale limestones. Similarly, on Anglesey, the unit consists of several hundred metre-thick intervals of well to poorly cleaved mudstone and intervening packages, of similar thickness, of sandstone and conglomerate. The mudstones are locally sandy, and some contain abundant thin to medium-scale beds of sandstone. The rocks in the vicinity of Llandovery and on Anglesey straddle particularly complex areas of folding and faulting, and the thickness of the thrust sheets that are interpreted to rest on the undivided Ordovician rocks in northern Anglesey is largely speculative.

4.2.3.14 Undivided Cambrian and Ordovician rocks — HSR

The undivided Cambrian and Ordovician rocks do not crop out within the area of interest, but they do occur at depth. North-east of Whitland, the unit refers to Tremadoc and Cambrian strata, whereas in the vicinity of Bangor and Conwy, it variably refers to strata up to the base of the Llanvirn or late Cambrian. In both areas, the rocks are confined above, below and laterally by other HSRs. Their position and depth is based on regional understanding of stratigraphy and structure and on the extrapolated thicknesses of overlying units. Consequently, they are poorly constrained. Confidence levels will necessarily decrease further in areas of greater structural complexity or towards major faults, where there may be dramatic thickness and facies changes.

This unit refers to those parts of the Cambrian and Ordovician successions that are poorly resolved because they are concealed and do not lie close to any relevant surface exposures or borehole provings. Details of their likely lithology are based on the nearest exposures of equivalent aged strata (see Howells, et al., 1985; Burt et al., 2012). Sandstones dominate the thick (>700 m) Cambrian succession in the vicinity of Whitland, but beds of mudstone (up to 100 m) and conglomerate (up to 50 m) are also present. The sandstones are variably micaceous and pebbly, and may be flaggy with interbeds of siltstone and silty mudstone. Tremadoc strata are not present everywhere, but may comprise several hundred metres of andesitic lavas and tuffs.

In the vicinity of Bangor and Conwy, the unit comprises two intervals of coarse-grained sedimentary rock, each up to several hundred metres thick, separated by a up to 600 m of very well-cleaved, silty mudstone with scant, thin sandstones. The lower, coarse-grained interval thickens westwards from 40 m to over 500 m and consists of conglomerates and sandstones. The upper, coarse-grained interval, of probable late Cambrian age, is dominated at its base by thick beds of coarse-grained sandstone, which pass upwards into mudstone and siltstone with sandstone laminae.

4.2.3.15 Late Cambrian, including Tremadoc, metasedimentary rocks — HSR

Late Cambrian and Tremadoc metasedimentary rocks essentially correspond to the Monian Supergroup on Anglesey and the Llŷn Peninsula. They are bounded to the south by a major shear zone, abutting it against Avalonian Proterozoic crystalline basement (an HSR), and to the north by another major fault, which abuts the Mercia Mudstone Group (an LSSR). Much of the Monian Supergroup lies within the depth range of interest, except in north-west Anglesey where it is believed to be too shallow. In southern and central Anglesey, it generally overlies Proterozoic HSRs and/or is faulted against them, except for inland of Moelfre where it is in contact with Devonian or younger strata that are not PRTIs. In contrast, in northern Anglesey, it forms a series of sheets which have been thrust over mostly Ordovician HSRs.

Whilst late Cambrian and Tremadoc metasedimentary rocks are generally well exposed they are structurally complex and correlation between separate areas is difficult because they host rather different successions, there is no biostratigraphical control and many of the mapped relationships defining the unit (as well as within the unit) are faulted (or tectonised). Hence, inferences about the unit’s subcrop are necessarily tentative and there is no supporting borehole or geophysical evidence: they are exclusively extrapolated from exposed relationships. Offshore data is limited, but samples from Holyhead Bay and beyond Amlwch confirm the presence of the Monian Supergroup off the shore of Anglesey (Jackson et al., 1995).

The Monian Supergroup comprises a succession of thick, indurated, anchizone to greenschist-grade (e.g. chlorite-mica schists) mudstone, sandstone and volcaniclastic-dominated units. These exhibit complex deformation structures and locally include laterally discontinuous horizons of metabasalt, metatuff and meta-ultramafic rocks. The supergroup has traditionally been subdivided into three groups — the Holy Island, New Harbour and Gwna groups — but, based on recent remapping, three alternative groups (in ascending order, the Holy Island, Llanfechell and Cemaes groups) are now recognised on Anglesey. In addition, strata in the south-east of the island that were formerly considered to be part of the Monian Supergroup are interpreted to be of Neoproterozoic age and now named the Pen-y-Parc Formation.

The Holy Island Group is largely dominated by sandstone lithologies while the overlying New Harbour Group is dominated by mudstone lithologies. The Gwna Group comprises a chaotic assemblage of clasts, blocks (up to several hundred metres diameter) and sediment rafts in a slaty mudstone and siltstone matrix; regional-scale variations in clast composition exist, and more coherently bedded units of interbedded sandstone, siltstone and mudstone are locally present (Gibbons and McCarroll, 1993), but the unit is too heterogeneous to be considered a PRTI. Consequently, it is excluded along the north coast of the Llŷn Peninsula.

4.2.3.16 Late Cambrian, including Tremadoc, Rocks — HSR

Late Cambrian and Tremadoc rocks fringe the southern half of Snowdonia National Park, form a narrow outcrop in the vicinity of Caernarfon and Bangor, and crop out as a series of fault-bounded inliers in Pembrokeshire. In the latter area, they are largely bounded by other HSRs, but in many parts of North Wales these rocks either lie below the depth range of interest or are bounded on at least one side by a rock type that is not of interest. For example, in the vicinity of Caernarfon and Bangor, these rocks are underlain by late

Cambrian sandstones and conglomerates that, because of the dip, bound the unit laterally. This may limit the potential of these rocks as a PRTI in this region.

The late Cambrian and Tremadoc rocks in Pembrokeshire may be up to 600 m thick and comprise coarse to fine-grained, flaggy sandstones that are thinly interbedded with siltstones and silty mudstones. Hence, they are not considered a PRTI in this area. In Snowdonia, they comprise up to 1700 m of interbedded silty mudstone and siltstone or fine-grained sandstone, the latter being more abundant in the upper half and near the base, although a regionally recognised unconformity at the base of the overlying Arenig locally removes late Cambrian and Tremadoc strata, leading to significant lateral variations in their thickness (Figure 25). Near the base, the sandstones are typically <10 cm thick (Pratt et al., 1995) and are subordinate to the mudstone, whereas in the upper half they dominate 2–30 m thick intervals that alternate with similar thicknesses of mudstone. Locally, the highest 100–150 m of the late Cambrian and Tremadoc rocks consist of pyritic mudstone.

In northern Snowdonia and in the vicinity of Caernarfon and Bangor, there are up to approximately 400 m of flaggy, silty mudstones with interbeds of laminated sandstone, which pass upwards into a few tens of metres of thick-bedded (about 0.5 m) coarse-grained sandstone and conglomerate. In Snowdonia National Park, there is an additional several hundred metres of well-cleaved, monotonous mudstone with one or more intervening sandstone-dominated intervals (each >100 m thick).

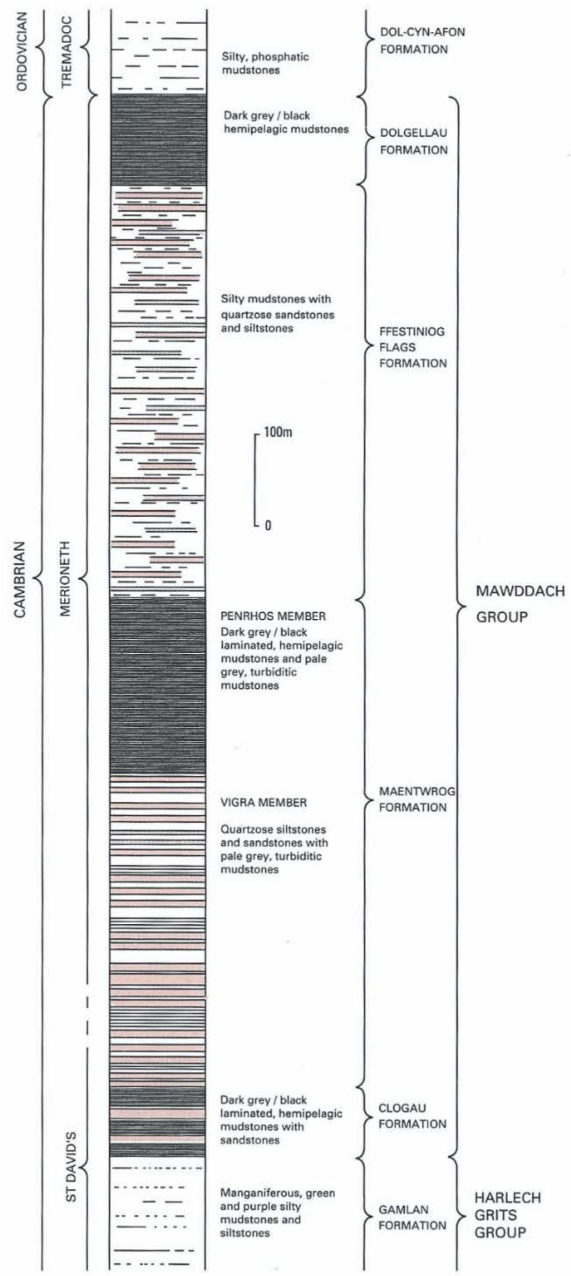


Figure 25 Generalised sequence of rock types in the late Cambrian (including Tremadoc) rocks (shown as ‘Merioneth’) of the Snowdonia National Park area; taken from Pratt et al. (1995), Fig. 4. British Geological Survey © UKRI 2018.

4.2.3.17 Undivided mid Cambrian rocks — HSR

Undivided mid Cambrian rocks form the core of central Snowdonia National Park to the east of Harlech, and crop out as a series of small, fault-bounded inliers in Pembrokeshire. In the former area, much of the unit either lies outside the depth range of interest or is bounded by a rock type that is not a PRTI: it is underlain by early Cambrian sandstones and conglomerates that, because of the dip or faulting, bound at least one side of the unit laterally. This may limit its potential as a PRTI in this region.

The mid Cambrian rocks in Pembrokeshire may be up to approximately 200 to 500 m thick. They predominately consist of various sandstone facies, but also include intervals of conglomerate (up to 30 m thick) and a well-cleaved, pyritic mudstone (up to 100 m thick). Nevertheless, because of the structural complexity of the area, they are not considered PRTI.

In Snowdonia National Park, the unit is up to 900 m thick and consists of 150–350 m thick intervals of siltstone or silty mudstones with variably spaced beds of coarse-grained sandstone (<0.1 m), separated by a 60–230 m-thick interval of pebbly sandstone, locally arranged into fining-up sequences. The mudstones are locally pyritic and/or manganiferous, and many of the sandstone-dominated units exhibit rapid lateral variations in thickness (Allen and Jackson, 1985). The top of the mid Cambrian rocks is defined by a 80–100 m-thick carbonaceous and pyritic mudstone, with only rare, thin sandstones, except locally (Pratt et al., 1995).

4.2.3.18 Undivided early Cambrian rocks — HSR

Undivided early Cambrian rocks crop out in comparatively small areas in central Snowdonia National Park, along the park's northern margin, on the coast to the south of Harlech, and in a series of narrow, fault-bounded inliers in Pembrokeshire. In North Wales the unit is both underlain and overlain by Cambrian sandstone and conglomerate units that are not PRTIs. Along the northern margin of Snowdonia National Park, the unit essentially corresponds to the Llanberis Slates Formation, whereas further to the south it corresponds to the Llanbedr Formation, which is largely concealed by superficial deposits in the area to the south of Harlech.

The unit is greater than 150 m thick in Pembrokeshire, where it predominately consists of micaceous sandstone with a basal conglomerate (up to 50 m thick), but includes units (up to tens of metres thick) of mudstone with numerous thin tuffs. Nevertheless, it is not considered a PRTI in this area because of the dominance of sandstones and the structural complexity. In central Snowdonia, the undivided early Cambrian rocks consist of well-cleaved mudstones (slates) with widely spaced thin siltstones; the unit doubles in thickness (to 180 m) at the coast, largely as a result of the presence of regularly interbedded sandstones in the upper part there. Along the northern margin of Snowdonia, the unit comprises up to 600 m of well-cleaved, silty mudstone with subordinate thin sandstones and siltstones.

4.2.3.19 Undivided early Palaeozoic rocks — HSR

This unit occurs widely across Wales, both onshore and offshore, much of it below the depth range of interest. Locally, however, and especially offshore (Tappin et al., 1994; Jackson et al., 1995) these rocks do occur within the depth range of interest: in the Bristol Channel and off the north coast of Wales, where they are overlain by (and interfolded with) rocks that are not of interest, and, offshore of Pembrokeshire, where they crop out on the seabed and abut (across major faults) other PRTIs. The largest area coinciding with the depth range of interest occurs in Tremadog Bay, where the unit is locally overstepped by rock types that are not of interest.

'Undivided early Palaeozoic rocks' describes sequences for which there is very little available information. Onshore, this is generally because of the lack of nearby equivalent exposures and the scarcity of available borehole information; offshore they have been proved in only one borehole (BGS Borehole 72/60), and are only tentatively identified in the scant seismic data.

The unit is likely to comprise several kilometres of rocks dominated, like the exposed onshore age-equivalent successions, by mudstones with interbedded sandstones and siltstones in varying proportions; thick but stratigraphically confined volcanic units are likely to be present locally. The succession is likely to thin dramatically towards the southern and eastern margins of the area of interest, accompanied by an increase in the proportion of sandstone. The Tremadoc strata sampled in BGS Borehole 72/60, in the Bristol Channel, comprise cleaved, micaceous mudstone. BGS Borehole 73/42, in Cardigan Bay, lies on the projected line of the onshore boundary between the Ordovician and Silurian strata and encountered an undated, hard, fractured, silty mudstone.

4.2.3.20 Neoproterozoic unnamed extrusive rocks (Padarn Tuff) — HSR

Acidic extrusive rocks of Neoproterozoic age are confined to two areas: one to the east of Bangor and Caernarfon, in North Wales, and the other in north Pembrokeshire. In both areas, the rocks are bounded by major faults and lie within the depth range of interest. In North Wales, the unit is mostly confined within the depth range of interest by overlying rock types that are not of interest.

Geophysical evidence indicates that all of Wales is underlain at depth by Proterozoic rocks (Chadwick and Evans, 2005); the distribution of extrusive Neoproterozoic rocks within the depth range of interest is poorly controlled and inferred entirely from rare surface outcrop. The presence of closely associated major faults in both North Wales and Pembrokeshire creates the potential for considerable complexity. The uniformity of the unit in North Wales, and its restriction to a north-east aligned tract, has led to the suggestion that it is essentially confined to a depression approximately 15 km wide and 60 km long (Howells et al., 1985). Field data indicate that the unit is at least 800 m thick in this area, and a gravity survey suggests that it is locally up to 2000 m thick.

The unit in North Wales consists of a uniform, strongly welded, acidic ash-flow tuff. In Pembrokeshire it exhibits greater variability, but largely comprises rhyolitic ashes, breccias and thin lavas. Those areas immediately to the north of Milford Haven are too small to be considered PRTIs and are excluded.

4.2.3.21 Undivided Neoproterozoic rocks — HSR

This unit, in combination with the unnamed Neoproterozoic extrusive rocks and the Avalonian Proterozoic crystalline basement, underlies all of Wales at depth and is exposed in a small number of isolated, fault-bounded inliers. These form parts of three tectonostratigraphical terranes (Figure 26): the Monian composite terrane, comprising Anglesey and the Llŷn Peninsula; the Wrekin terrane, comprising the area to the south and east of a line between Carmarthen and the Long Mynd (Shropshire), and the Cymru terrane, comprising Pembrokeshire, Mid Wales and North Wales.

The largest exposures of the unit occur on Anglesey, where it occupies a series of major fault-bounded blocks and is locally intruded by Neoproterozoic granite. The unit is bounded by rocks ranging in age from Cambrian (an HSR) to Carboniferous (not a PRTI), and frequently occurs in the depth range of interest.

The exposures in Pembrokeshire and in the vicinity of Carmarthen are small and the unit mostly lies below the depth range of interest; the unit is entirely concealed in the vicinity of Builth Wells and, although much of it lies within the depth range of interest, it is overlain by non-PRTI rock types.

Undivided Neoproterozoic rocks have limited exposure, are structurally complex and lack biostratigraphical markers, so their relationships to one another and their spatial variability are not well understood. Regional geophysical evidence (Chadwick and Evans, 2005) suggests that, except locally, they generally occur below the depth range of interest and are dissected by major faults (including shear zones) which, based on exposed relationships, may have significant displacements (Gibbons and McCarroll, 1993). Presumed Neoproterozoic rocks were recorded in the Bryn-teg Borehole (Allen and Jackson, 1978), but are otherwise unknown in mainland North and Mid Wales. Understanding of the rocks comprising the Wrekin terrane is partly based on exposures outside of Wales, in the Welsh Borderlands.

The unit generally comprises a variable mix of mostly greenschist-grade metasediments, volcaniclastic sediments, tuffs and intrusions; deformation is widespread and carbonates are scant. The succession is likely to be several kilometres thick. The Wrekin terrane comprises calc-alkaline and gabbroic intrusions, bedded volcanics, metasedimentary quartzites and schists (Wilby, 2004), and thick mudstone and sandstone-dominated sequences, which are around 6 km thick at Long Mynd and have a broadly coarsening-up trend (Carney et al., 2000). The Cymru terrane comprises a thick volcanic pile of basic lava and tuff interbedded with acidic pyroclastics and volcaniclastics and subsidiary mudstones, intruded by relatively small granites and minor basic sheets. A sequence over 1 km thick occurs in the small inlier near Llangynog, and the Bryn-teg Borehole proved 140 m of basic and intermediate lavas and tuffs, and volcaniclastic mudstone, siltstone and sandstone, intruded by thin, basic dykes and sharply overlain by Cambrian strata.

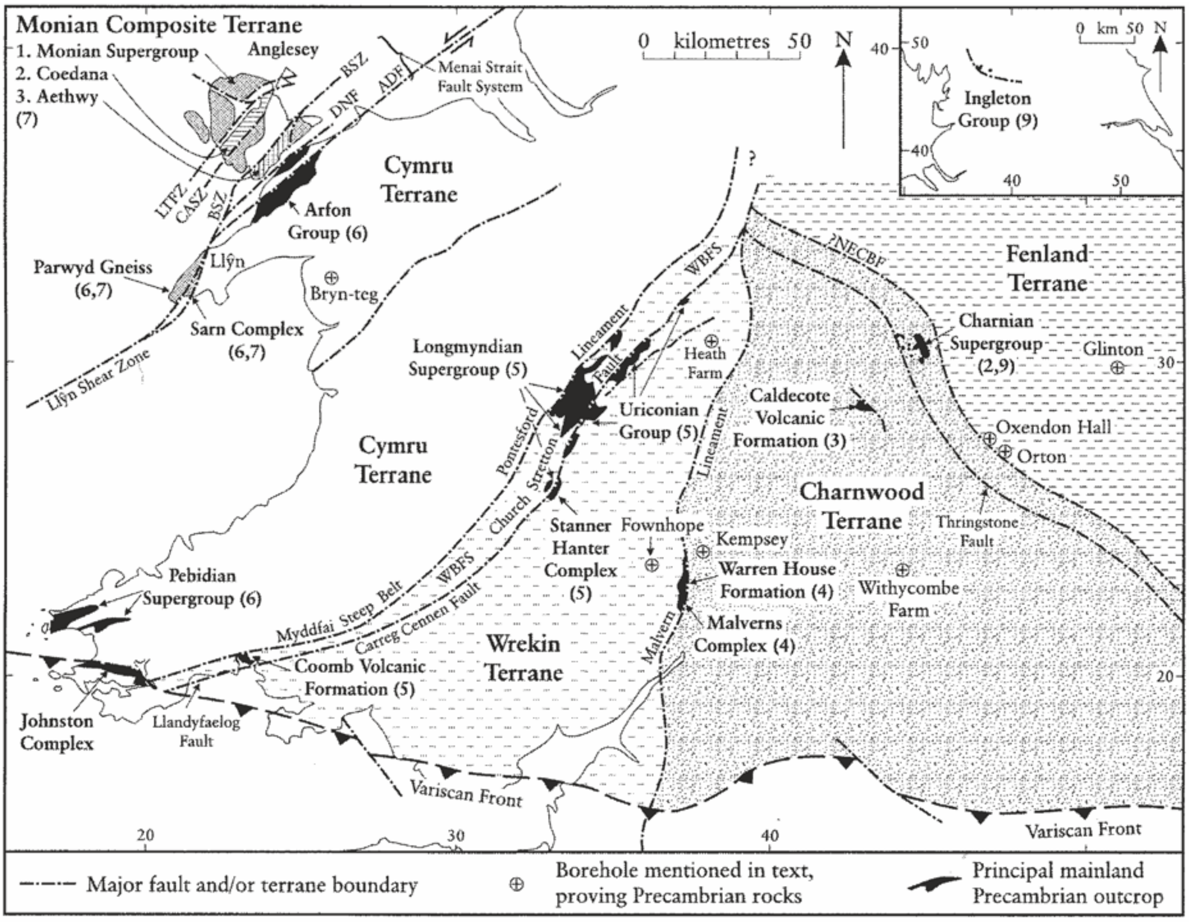


Figure 26 Simplified boundaries of the tectonostratigraphical terranes forming the basement of Wales, and the distribution of the key boreholes and inliers proving them; taken from Carney et al. (2000), Fig. 1.1. DNF = Dinorwic Fault; ADF = Aber–Dinlle Fault; BSZ = Berw shear zone; CASZ = Central Anglesey shear zone; LTFZ = Llyn Traffwll fault zone. WBFS = Welsh Borderland Fault system. British Geological Survey © UKRI 2018.

The Monian composite terrane (Greenly, 1919) is structurally complex and divided into several domains, each separated by major faults. It crops out most widely in south and central Anglesey — forming the Coedana complex and the Central Anglesey and Berw shear zones — but inliers in the north-east suggest that it is present at depth further north, at least locally. It comprises a heterogeneous sequence of high-grade metamorphosed, migmatitic pelites and subordinate metasandstones, impure carbonates, and basaltic intrusions or lavas; a 5 km-wide tract of blueschist-facies metabasalts and sediments with intense foliation and isoclinal folding occurs in the south, and a fine-grained hornfels is associated with the major granite intrusion in the centre.

4.2.3.22 Avalonian Proterozoic crystalline basement — HSR

This unit, in combination with the unnamed Neoproterozoic rocks and extrusive rocks, forms the basement of Wales. Its most extensive exposures are on the Llŷn Peninsula and in central Anglesey, where it occupies north-west-oriented tracts; the areas present in Pembrokeshire are too small to be considered PRTIs. These form component parts of the structurally complex Monian composite and Cymru terranes respectively.

The unit lies within a narrow shear zone on the Llŷn Peninsula and, at the depth range of interest, abuts HSRs on its southern margin; to the north it abuts rock types that are not of interest. South-west of Caernarfon it largely lies below the depth range of interest, but to the south-east and north-east of here it is closely associated with unnamed Neoproterozoic extrusive rocks and lies within the depth range of interest (together with other, Cambrian and younger, HSRs).

Avalonian Proterozoic crystalline basement rocks occur within the depth range of interest across much of Anglesey, where they are generally faulted against (and/or overlain by) Cambrian and Ordovician HSRs; an exception is the tract inland of Moelfre, where the unit is overlain by Devonian and younger strata that are not PRTIs. In Pembrokeshire, the unit intrudes fault-bounded tracts of unnamed Neoproterozoic extrusive rocks and is locally overlain by (or abuts) Cambrian and Ordovician rocks, which are themselves HSRs.

The position of Avalonian Proterozoic crystalline basement in central Snowdonia National Park is entirely conjectural, because the Bryn-teg Borehole only intersected a Neoproterozoic cover sequence. Across the majority of Wales it lies below the depth range of interest.

The Avalonian Proterozoic crystalline basement has a very limited distribution at surface, typically within structurally complex areas and, on the Llŷn Peninsula, it is largely concealed beneath superficial deposits. Outside of these areas it is generally concealed beneath a thick cover of early Palaeozoic strata, and has not been proved in boreholes. Available data is limited to deep regional geophysical surveys, which suggest considerable structural complexity, including the presence of major faults (Chadwick and Evans, 2005). Consequently, the depth and character of these rocks are poorly constrained across much of Wales, and their modelled distribution is largely inferred from regional-scale structural reconstructions. For example, its relatively shallow and widespread distribution beneath Anglesey is largely inferred from the presence of isolated inliers to the north of the main exposure in the centre of the island.

The unit variably consists of granites, granodiorites or bimodal suites of gabbro-diorite, locally altered to greenschist facies or foliated and gneissic (Gibbons and McCarroll, 1993). On Anglesey, it is comprised of granite, converted into a protomylonite, with a fine-grained hornfelsed aureole. Note: the Twt Hill granite, north-east of Caernarfon, has recently been shown to be part of the Avalonian Proterozoic crystalline basement (Schofield et al., 2008) rather than the Ordovician felsic intrusion PRTI, as is currently displayed in the model. It lies within a narrow shear zone (approximately 3 km wide) and is hosted by the Padarn Tuff, itself an HSR.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in Wales and shows their surface extent on a map (Figure 27). Many of the structures are well known and are identified in the BGS regional guides and memoirs. As described in the guidance (RWM, 2016a), they are relevant to safety in two ways: they may provide effective limits to any rock volume being considered for siting a GDF, and they have an impact on the uniformity and predictability of rocks and groundwater at a scale of relevance to a GDF.

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

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

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

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

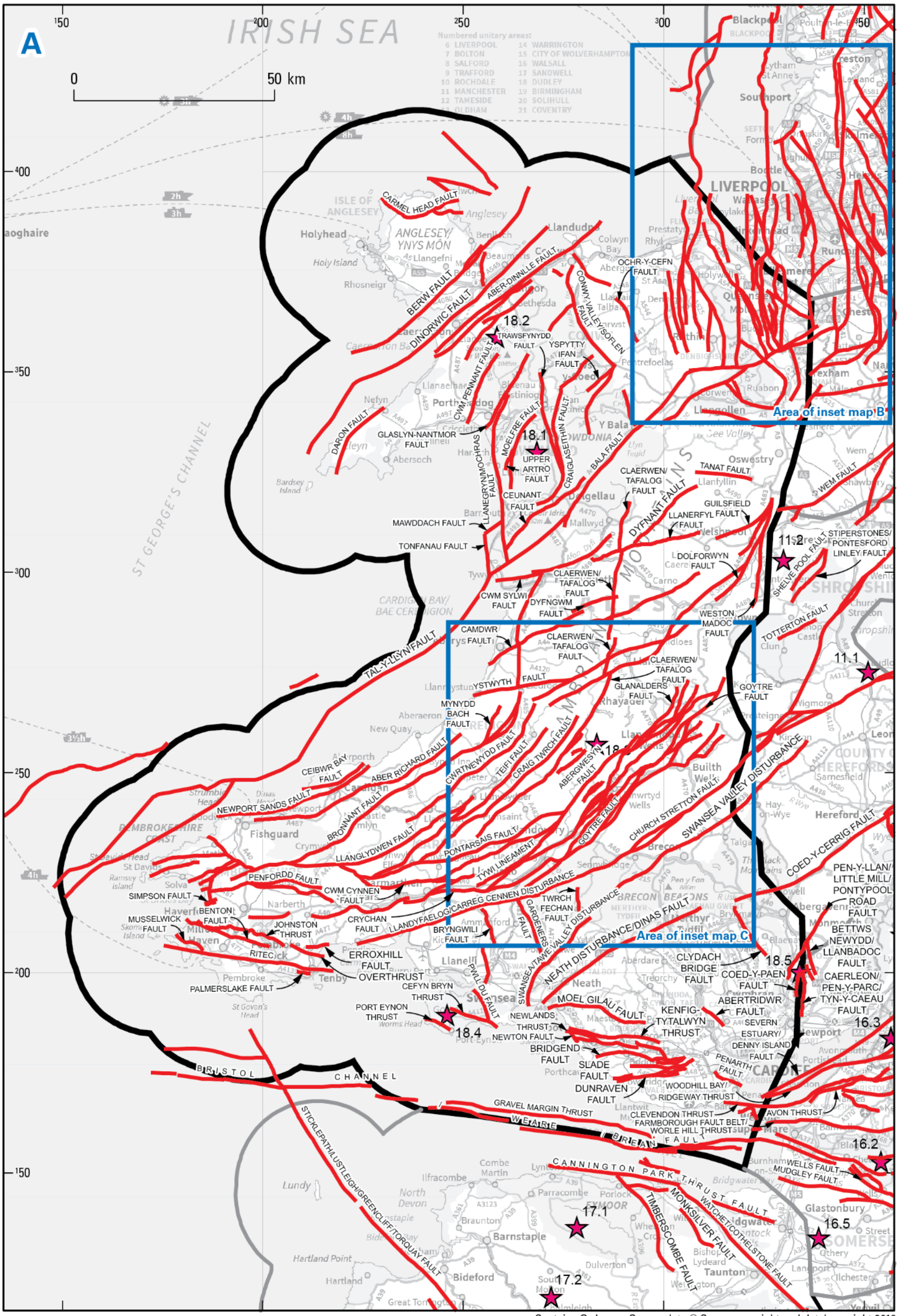
With the exception of Mesozoic younger cover successions underlying the Vale of Clwyd, offshore Cardigan Bay, the East Irish Sea and the Bristol Channel, Wales is underlain by Palaeozoic basement and older cover rocks that have largely been influenced by repeated cycles of tectonic shortening, extension and redistribution. As a result they are locally pervasively folded and transected by a complex network of faults of various orientations.

The main events are as follows.

> Latest Precambrian folding and shearing of Precambrian rocks, thought to be associated with accretionary tectonics around the margin of Gondwana in locally preserved, metamorphic successions of Anglesey in North Wales.
>
> Early Palaeozoic Caledonian basin subsidence, inversion and shortening that culminated in the Mid Devonian Acadian Orogeny, which formed Wales's main structural grain. During this episode the Welsh basin was inverted, tectonically shortened and subject to very low-grade metamorphism. The Acadian phase imposed a series of largely north-east-trending periclinal folds, formed a locally pervasive, slaty cleavage and propagated or reactivated belts of steep, typically north-east to south-west-oriented faults. In addition, a north–south fault set was reactivated in North Wales, which is thought to have controlled the earlier volcanic phases (Dunkley, 1979). These are locally cross cut by a sparse, east–west–east-trending fault set.
>
> The late Palaeozoic Variscan Orogeny most strongly affected the southern parts of Wales. A putative line, the Variscan front, marks the limit of pervasive deformation, crosses the Bristol Channel and South Wales following a west-north-west trend across Swansea Bay and Carmarthen Bay. To the south of the front, on the Gower Peninsula and in south Pembrokeshire, late Palaeozoic older cover rocks have been strongly folded and shortened into a north-verging imbricate thrust fan (e.g. Hancock et al. 1983); north of this they are only weakly deformed.

Following this tectonic episode, a series of rift zones developed as plates began to disperse. At this time, much of Wales formed a resistant, upland region, around the margins of which extensional stresses drove formation of the graben-like East Irish Sea, Worcester and Cheshire basins during Permian and Triassic times (Chadwick and Evans 2005).

A more comprehensive account of the structural evolution of the British Isles is presented in Appendix A (Pharaoh and Haslam, 2018).



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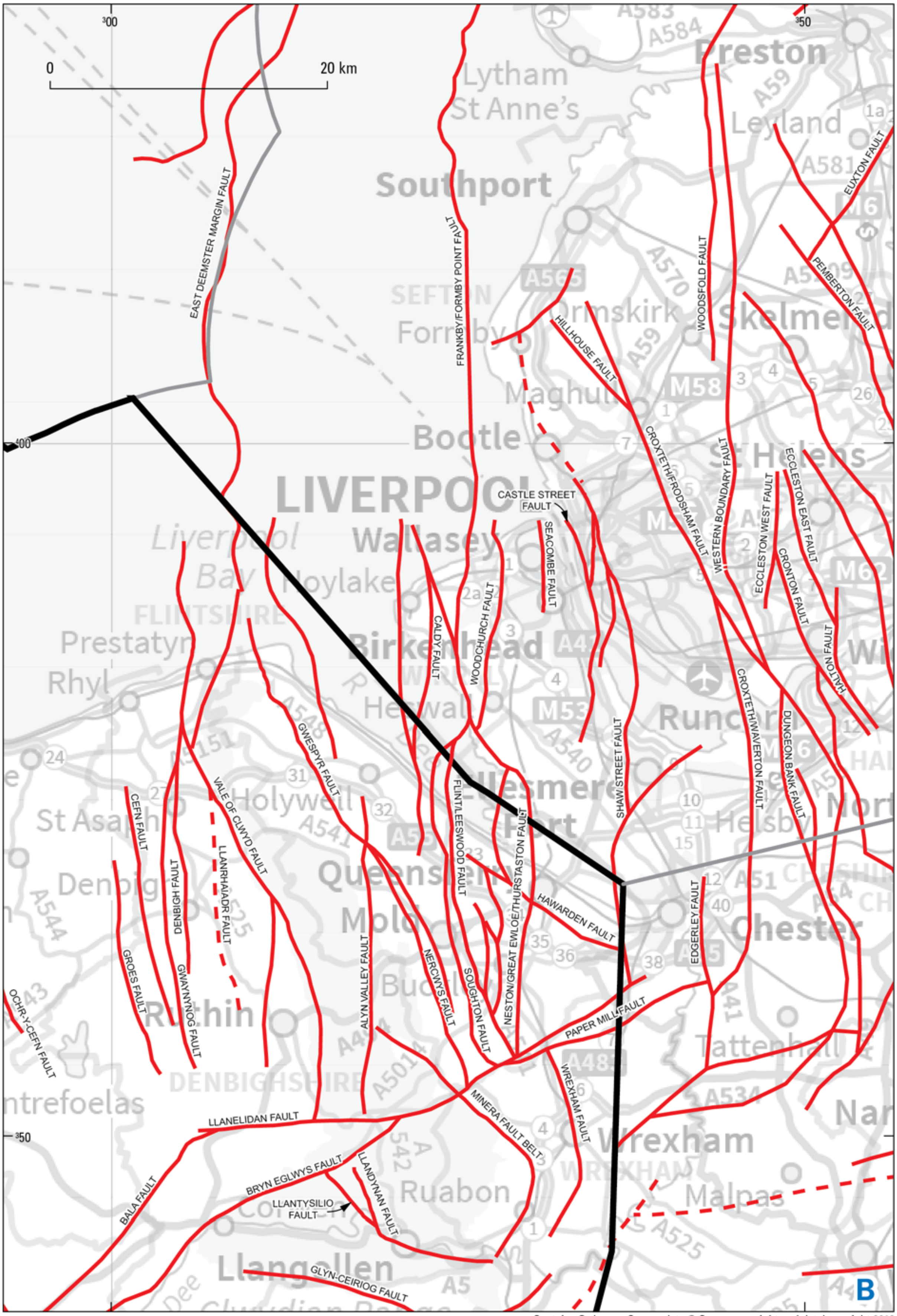
★ Areas of folding

Wales and adjoining areas

Major faults transecting depth of interest

Major fault terminating in depth of interest



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Areas of folding

Major faults transecting depth of interest

Major fault terminating in depth of interest

Wales and adjoining areas

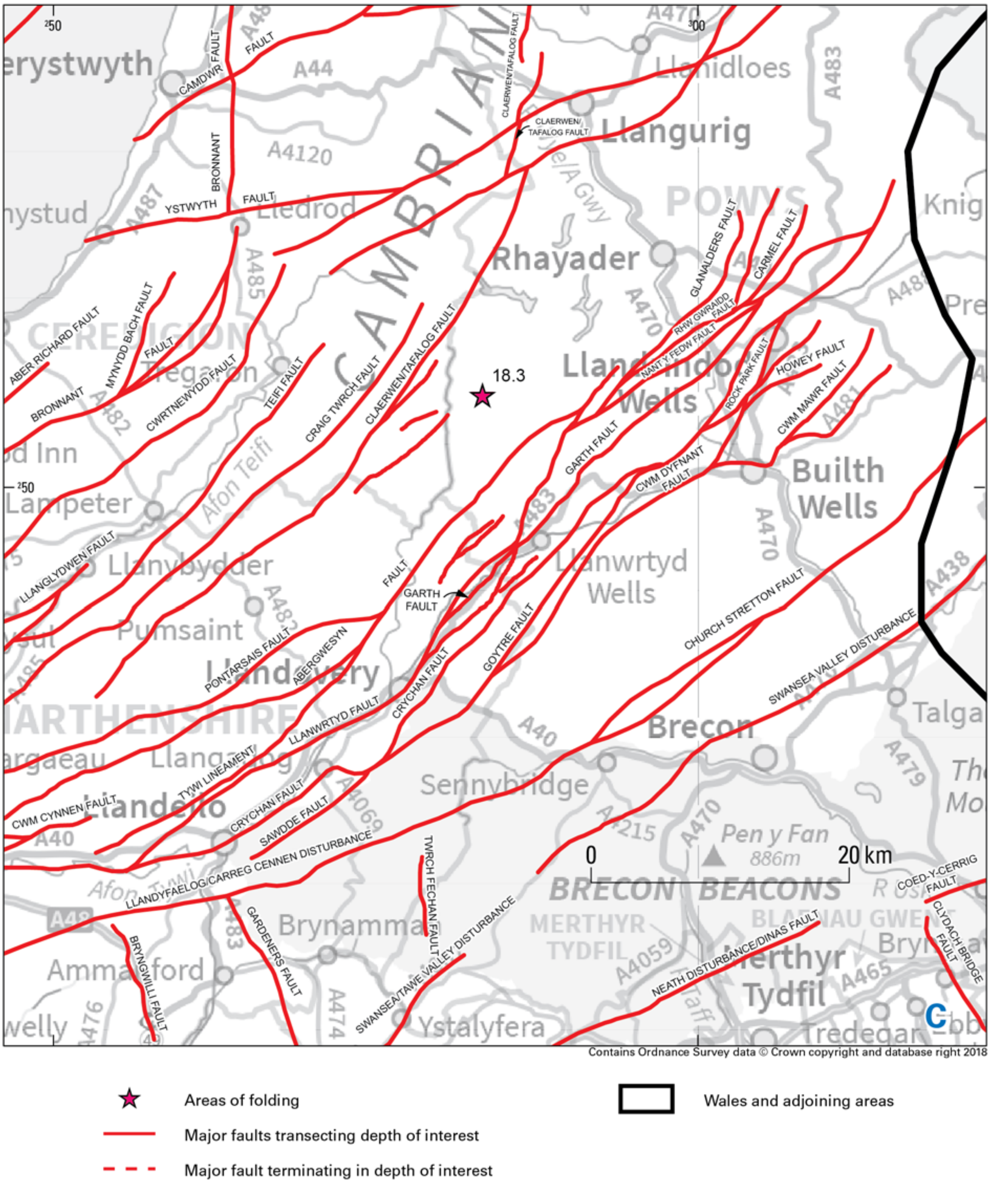

Figure 27 A) Major faults and areas of folding in Wales. B and C) are inset maps. Area of the inset maps are shown on A. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

5.3 MAJOR FAULTS

The major faults selected from analysis of the UK3D model and published maps in Wales exhibit a variety of orientations and evolutionary histories as a consequence of the complex structural history described (Figure 27). In this description, the major faults are described in terms of local fault plexuses:

- the Welsh Borderland fault system
- the Central Wales Syncline

- the South Wales Variscan fault and fold belt
- the northern Welsh basin
- Anglesey and the Menai Strait fault system

Each plexus contains a set of faults with comparable orientations and structural histories, reflecting the analogous response of similarly oriented faults planes to extension or compression in the contemporaneous regional stress field. Where evidence for the siting and character of these structures is known, it is described in brief.

Where folding is directly related to faulting, e.g., an anticline associated with a reactivated blind fault or as fault drag on the flanks of the fault, these are described with the controlling fault. More general folding is described following the description of the faulting.

5.3.1 Welsh Borderland fault system

The Welsh Borderland fault system comprises the north-east-trending plexus of fault structures that broadly lies along the south-east margin of the thick, sedimentary succession of the early Palaeozoic Welsh basin (Figure 16) approximately extending from the Welsh Borderland around Llanbister, through Builth Wells and Llandovery out to the south coast at Carmarthen Bay. For the purpose of this account it includes the Coed y Cerrig Fault and the Neath disturbance in the south-east and the Abergwesyn Fault in the north-west. The zone is contiguous with the Pontesford lineament of the Welsh Borderlands and extends to the west-trending Cwm Cynnen Fault in south-west Wales. The Welsh Borderland fault system is often referred to as the Tywi lineament and is also coincident with the Tywi Anticline (compare with Jones, 1912).

The Welsh Borderland fault system is broadly coincident with the geophysical anomaly that defines the edge of the Midlands platform or microcraton to the south-east, broadly separating regions of thick early Palaeozoic sediment accumulation from the more condensed successions of the Welsh Borderlands (see adjacent Welsh Borderlands region report). The Welsh Borderland fault system contains a number of inliers of Precambrian rocks and Mid Ordovician volcanic rocks, and preserves dramatic facies changes that record the contemporaneous, basinward, shelf-to-slope apron transition. Because of these features, the fault system has long been considered the site of repeated fault reactivation that had a strong influence on patterns of sedimentation (e.g. Woodcock, 1984; Woodcock and Gibbons, 1988; Davies et al., 1997).

The fault system comprises numerous named and unnamed fault strands. Those identified from UK3D and BGS geological maps include (from south-east to north-west): the Coed y Cerrig Fault; the Neath disturbance; the Swansea (Tawe) valley disturbance; the Llandyfaelog–Carreg Cennen disturbance; the Church Stretton Fault; the Erroxhill Fault; the Cwm Mawr Fault; the Cwm Dyfnant Fault; the Carmel Fault; the Rhw Gwraidd Fault; the Glanalders Fault; the Howey Fault; the Rock Park Fault; the Goytre Fault; the Sawdde Fault; the Crychan Fault; the Tywi lineament; the Cwm Cynnen Fault; the Garth Fault; the Nant y Fedw Fault; the Llanwyrtyd Fault; the Abergwesyn Fault, and the Pontarsais Fault.

These faults are described or mentioned in a number of BGS publications, in particular the sheet explanations for the Builth Wells, Llandovery and Newcastle Emlyn districts and the Llanilar and Rhayader memoir (Schofield et al., 2004; Schofield et al., 2009; Wilby et al., 2007; Davies et al., 1997) as well as the coalfield memoirs for Swansea, Pontypridd and Abergavenny (Barclay, 1989, 2011; Woodland and Evans, 1964), which form the basis of this account.

These structures were largely devised to account for contacts between lithostratigraphical units during the 1:25 000 scale primary geological survey. Because of this, their offset is largely explained in terms of vertical movements, although some authors have also argued that some of these structures also accommodated a component of lateral displacement (e.g. Woodcock, 1984; Woodcock and Gibbons, 1988). There are no direct observations of fault displacements in the Welsh Borderland fault system and no recorded descriptions of fault rocks. Faults in the fault system are assumed to comprise zones of shattered and weak rock and are typically mapped in valleys.

While the majority of these individual faults transect strata of early Palaeozoic age, the Coed y Cerrig Fault/Neath disturbance, Swansea (Tawe) valley disturbance and Carreg Cennan disturbance transect deformed, late Palaeozoic strata providing evidence for movement that post-dates Variscan folding and thrust translation.

There are no recorded direct observations of fault rock for the Neath disturbance and contiguous Coed y Cerrig Fault, although they are described to comprise a complex zone of north-east-trending faults with vertical and lateral displacements associated with impersistent north-east-trending folds (Owen, 1953).

Displacement is interpreted to be between 15 and 200 m vertical, down-to-north throw with lateral displacement of up to 1200 m based on interpretation of surface geological mapping (Owen and Weaver, 1983). The Swansea (Tawe) Valley Fault comprises a belt of north-east-trending faults located in the Swansea valley, reported to be up to around 2 km in width and associated with locally developed folds (Weaver 1975). A component of down-to-north-west, vertical displacement is reported as between 30 and 550 m, while sinistral transcurrent displacement of 280 m is also reported (Owen and Weaver 1983). The Carreg Cennan disturbance (also known as Llandyfaelog disturbance at its western extent) comprises a south-west extension of the Church Stretton Fault and has locally been described in detail. For most of its length it transects Devonian Old Red Sandstone facies but locally entrains units of Carboniferous limestone on its north side and as such preserves a similar age movement history to the Neath disturbance and Swansea (Tawe) Valley Fault. It is described as comprising a number of, or locally a single, north-east-tending vertical faults, downthrown to the north, with estimates of vertical displacement ranging from 20–400 m and sinistral lateral displacement between around 200 and 500 m (Owen and Weaver, 1983) and possibly as great as 1200 m (Trotter, 1947). The Swansea (Tawe) Valley Fault is associated with locally developed fold structures. Trotter (1947) also suggests that the vertical movement was associated with thrusting, consistent with the overall Variscan tectonic motif.

5.3.2 Central Wales Syncline

The Central Wales Syncline, also known as the central Wales lineament (Jones, 1912) comprises a broad, faulted, synclinal structure located in central Wales, broadly underlying the Cambrian Mountains between Llanidloes and Lampeter, and is contiguous with the Llandderfel Syncline to the north-east. Associated with this, and extending offshore into Cardigan Bay, are a plexus of north-east-trending faults that, in common with those of the Welsh Borderland fault system, transect early Palaeozoic rocks and are implicated in strongly influencing patterns of sedimentation, particularly during early Silurian times (e.g. Davies et al., 1997; 2003).

The Central Wales Syncline comprises numerous named and unnamed fault strands. Those identified in UK3D include (from east to west): the Weston Madoc, Dolfordwyn, Dyfnant, Claerwen, Craig Twrch, Teifi, Llanglydwen, Cwrtnewydd, Penfordd, Bronnant, Mynydd Bach, Aber Richard, Newport Sands and Ceibwr Bay faults. The north-western margin of this fault set is defined by the Llanelidan, Paper Mill, Bryn Eglwys, Ceunant and Bala faults and their possible offshore extension in Cardigan Bay, the Tal-y-Llyn Fault. An additional set of east-north-east-trending faults that apparently crosscuts the main north-east set includes the Guilsfield, Cwmsylwi, Camdwr, Dyfngwm, Glyn-Ceiriog, Llantysilio, Llandynan, Llanerfyl and Ystwyth faults, as well as the Tanat Fault located on the southern flank of the Berwyn dome.

These faults are mentioned in a number of BGS publications, in particular the memoirs for the Rhayader and Llanilar, Aberystwyth and Cadair Idris districts (Davies et al., 1997; Cave and Hains, 1986; Pratt et al., 1995) as well as sheet explanations for the Llandovery, Lampeter, Newcastle Emlyn, Llangranog, Cardigan and Fishguard districts (Schofield et al., 2009, Davies et al., 2003, 2006a, 2006b; Wilby et al., 2007; Burt et al., 2012) that are used to inform this account.

These structures are largely devised to account for contacts between lithostratigraphical units during the 1:25 000 scale primary geological survey. Because of this, their offset is largely explained in terms of vertical movements. There are no direct observations of fault displacements in the Central Wales Syncline and, with a few exceptions, no recorded descriptions of fault rocks. Faults in the Central Wales Syncline are assumed to comprise zones of shattered and weak rock and are typically mapped in valleys.

Of the north-east-trending faults, the Bronnant Fault and adjacent Aber Richard Fault are notable for confining about 2500 m of Silurian, coarse, clastic turbidites on their north-west side but were reactivated during the Acadian phase of deformation and now form the focus of a significant divide between north-west and north-east-inclined, slaty cleavage belts (e.g. Davies et al., 2006a; b). Similarly the Clearwen Fault and Craig Twrch Fault are thought to have been responsible for confining deposition of up to 1500 m of coarse, clastic, Silurian turbidites (e.g. Davies et al., 2006b; Schofield et al., 2009). Along with the Llanelidan Fault, the Bala Fault is one of a series of structures that define the northern margin of the southern Welsh basin and is known from outcrops of shattered, slickensided and kinked mudstone and fault breccia outcrops in the Tal-y-Llyn Pass (Pratt et al., 1995). The Bala Fault is largely downthrown to the south with variable throw, estimated to be as much as 7 km (Pratt et al., 1995).

Geometric relationships between minor fold structures and component faults have led authors to infer both a significant component of vertical and transcurrent movement. A proposed offshore extension, the normal, north-west-dipping Tal-y-Llyn Fault, is described offshore in Cardigan Bay based on seismic data, where it confines the distribution of the Permo-Triassic North and South Celtic Sea basins along their south-east margins (Tappin et al., 1994). The Llanelidan Fault locally truncates the southern margin of the Vale of Clywd half-graben, is downthrown to the north and appears to be a normal fault that preserves thicker developments of late Palaeozoic and Mesozoic strata in its hanging wall (Smith and George, 1961).

The east-north-east-trending faults are described in the Llanilar district (Davies et al., 1997) as being steeply inclined, displaying normal offsets downthrown to either the north-north-west or the south-south-east. Shallow-plunging slickensides have locally been observed that imply an oblique component in some areas. The Ystwyth Fault itself lies within a marked topographical depression, the Ystwyth valley. It is estimated to preserve around 1300 m of sinistral, transcurrent movement and 300 m of vertical downthrow to the north and is locally associated with formerly economic vein mineralisation.

5.3.3 Variscan fault and fold belt

The Variscan fault and fold belt broadly describes the assemblage of west-north-west-trending folds and faults that extend from the Bristol Channel northward toward St Bride's Bay and largely affects late Palaeozoic older cover rocks, including the less strongly deformed Carboniferous Coal Measures of the South Wales coalfield that lie in the foreland region. Many of the faults in this region are interpreted to have a reverse sense of displacement and formed in association with folds during the main Variscan event. Included in this are a small number of north to north-north-west-trending faults that crosscut Variscan folding.

There are numerous named and unnamed fault strands. Those that are significant to this study include, from south to north: the Central Bristol Channel Fault; the Penarth, Dunraven, Slade and Bridgend faults and Newlands Thrust of the Vale of Glamorgan; the Cefyn Bryn and Port Eynon thrusts and the Moel Gilau Fault of Swansea Bay; the Ritec, Musselwick, Simpson, Newton, Palmerslake and Benton faults, and the Johnston Overthrust and Kenfig–Tytalwyn Thrust, of Pembrokeshire. The significant north to north-north-west-trending faults include the Abertridwr Fault; Clydach Bridge Fault; the Gardeners Fault; the Twrch Fechan and Pwll Du faults that transect the South Wales Coalfield Syncline; the Coed-y-paen, Bettws Newydd and Pen-y-llan–Little Mill–Pontypool Road faults flanking the early Palaeozoic rocks of the Usk Antiform, and the Bryngwilli Fault in the western part of the coalfield.

Faults from the Vale of Glamorgan and Swansea Bay are locally exposed in coastal sections and are described in BGS memoirs and sheet explanations for the Cardiff, Bridgend and Swansea districts (Waters and Lawrence, 1987; Wilson et al., 1990; Barclay, 2011). The Pembrokeshire faults are described from good coastal outcrops that have been synthesised by Hancock et al. (1983).

In contrast, the offshore Central Bristol Channel Fault is constrained by interpreted seismic reflection data. This fault has been interpreted to extend onshore to the south as faults that control the northern margin of the west Somerset basin (Miliorizos et al., 2004). The fault is imaged as dipping toward the south, with an eastern trend and a proposed Mesozoic normal displacement of about 1500 m, downthrown to the south and juxtaposing Jurassic against Triassic strata at the seabed (Brooks et al., 1988). It has been interpreted as a reactivated Variscan thrust, perhaps as a hanging-wall shortcut to the Gravel Margin Thrust (Miliorizos et al., 2004). There is some debate on the amount of displacement, dependent upon the interpretation of a seismic reflector to the south of the thrust as either top Carboniferous Limestone Supergroup (Smith et al., 1998), or as early Palaeozoic or Precambrian (Miliorizos et al., 2004).

There is little information available regarding the Penarth Fault of the Cardiff district other than it displaces strata of Permo-Triassic age and is known from mapping to be downthrown to the north (Waters and Lawrence, 1987). Similarly, there is little information about the Bridgend, Dunraven and Slade faults of the Bridgend district, although they are said to be Variscan thrusts that have been reactivated as apparent normal faults and disrupt strata of late Palaeozoic and Mesozoic age. Small-scale structures seen at the outcrop of the Dunraven Fault provide some evidence for local transcurrent movements (Wilson et al., 1990).

The Newlands Thrust transects Carboniferous Coal Measures strata. It is known from underground coal workings and is largely concealed by Quaternary superficial deposits at the surface. Where observed, it dips moderately toward the north and has an offset of around 230 m interpreted as evidence for southerly directed thrusting of Lower Coal Measures strata over Middle Coal Measures strata (Woodland and Evans, 1964; Barclay, 2011). The Moel Giau fault is also known in underground coal workings. It is interpreted as a normal fault, downthrown to the south and juxtaposing younger Carboniferous Warwickshire Group rocks against Middle and Lower Coal Measures. The displacement is estimated to be between around 60 and

600 m (Woodland and Evans, 1964). The Cefyn Bryn Thrust of the Gower Peninsula is interpreted as a northerly directed thrust fault known from mapping (George, 1940). At surface it juxtaposes older Devonian Old Red Sandstone facies over younger Carboniferous limestone facies. There are no published estimates of the amount of fault displacement.

The Ritec Fault of Pembrokeshire is the southernmost of a plexus of west-trending structures interpreted as Variscan thrust faults that are identified for this study (e.g. Hancock et al., 1983). At surface, the Ritec Fault locally juxtaposes Devonian Old Red Sandstone facies against Carboniferous limestone facies. Although not exposed, the fault is interpreted to dip steeply toward the south and with a displacement of between 100 and 1000 m (Hancock et al., 1983). It is also implicated in controlling patterns of sedimentation both in confining the distribution of Devonian strata and accommodating Carboniferous subsidence (Hillier and Williams, 2007; Sullivan, 1964).

The Musselwick Fault is described by Hancock et al. (1983) as a steeply south-dipping fracture zone juxtaposing Ordovician strata to the south against Devonian Old Red Sandstone facies to the north. Oblique slickensides indicate local sinistrally oblique–reverse slip with an offset that ranges from 0 to 1500 m.

At surface, the Benton Fault juxtaposes Devonian Old Red Sandstone facies against Precambrian rocks, but does not apparently penetrate Carboniferous limestone facies to the east. The pre-Carboniferous displacement is said to exceed 1500 m, downthrown to the north, and may have controlled sediment distribution patterns (Hancock et al., 1983).

The Johnston Thrust can be seen in coastal section at the south of St Bride’s Bay. It dips gently toward the south and, at surface, thrusts Precambrian strata northward over Carboniferous Coal Measures. The (reverse) throw is estimated to vary between 500 and 3000 m. Complex patterns of folding fabric development are also developed local to the fault (Hancock et al., 1983).

The Simpson Fault (or Druidston Haven North Fault) bounds the northern margin of the Druidston Haven horst where mid Ordovician strata are juxtaposed at surface against Carboniferous Coal Measures. The fault is exposed in the central part of St Bride’s Bay where it dips toward the north and has a normal sense of displacement with downthrow toward the north (Owen, 1974; Tringham, 1980). The downthrow of this fault was estimated to be around 1800 m where Warwickshire Group rocks are juxtaposed against Ordovician strata (Cantrill et al., 1916).

Of the north to north-north-west-trending faults, the Clydach Bridge Fault transects the Carboniferous Coal Measures strata with associated splays shown on mapping as extending to the northern margin of the Carboniferous crop. This fault is estimated to have a normal throw of up to around 62 m, is downthrown to the west and, where observed in opencast and underground workings, dips moderately toward the west (Barclay, 1989). The Abertridwr Fault also transects Carboniferous Coal Measures strata where it is known from underground workings. It dips steeply to the east and is downthrown on its eastern side by up to around 55 m (Squirrell and Downing, 1969). The Bryngwilli Fault is reported as being downthrown to the west (Strahan et al., 1907). No estimates of amount of displacement are reported, although mapping illustrates that it largely transects Carboniferous Coal Measures at surface, while at its northern extent it juxtaposes Carboniferous limestone and Devonian Old Red Sandstone facies. These faults are three examples of numerous ‘cross faults’ that transect the South Wales coalfield. These are generally interpreted in terms of normal displacements based on observations of stratigraphical offset at outcrop in underground coal workings.

The Pontypool Road, Pen-y-llan and Little Mill faults form a plexus of structures that define the northern boundary of the Usk Anticline and juxtapose early and late Silurian strata at surface. The vertical downthrow on these faults is to the north and estimated to be up to around 365 m, while various estimates of sinistral transcurrent movement range between 200 and 1000 m. The Betws Newydd Fault (Barclay, 1989) is described as an ill-defined extension of the Llanbadoc Fault that juxtaposes older and younger Silurian strata along the eastern flank of the Usk Anticline, with downthrow to the east estimated at up to 150 m. The Coed-y-paen Fault lies on the western flank of the anticline and similarly juxtaposes older and younger Silurian strata. It preserves around 80 m or downthrow on its western side (Squirrell and Downing, 1969).

5.3.4 Northern Welsh basin

The northern Welsh basin (Figure 16) is dominated by sedimentary rocks of Cambrian and Ordovician age in the west, with several thick units of Ordovician volcanic and intrusive igneous rocks. Younger Silurian rocks are exposed at the surface toward the east, unconformably overlain by a Carboniferous succession in the far east of the area and Permo-Triassic rocks that are confined within a narrow, fault-bounded basin in the Vale of Clwyd. The faults described herein are largely approximately north, north-north-east or north-north-west-trending and are a subset of many named and unnamed structures that are known from surface mapping. With the exception of the Vale of Clwyd and Tremadoc Bay surveys, there have been no geophysical investigations in the region that further constrain structure in the subsurface (Warren et al., 1984).

Named faults that transect the Cambrian and Ordovician strata include the Cwm Pennant fracture, and the Glaslyn–Nantmor, Llanegryn (Mochras), Moelfre, Upper Artro, Yspytty Ifan, Trawsfynydd and Craiglaseithin faults. Further to the east, the Conwy Valley–Soflen Fault juxtaposes mid Ordovician and Silurian strata. Silurian, Carboniferous and Permo-Triassic strata are transected by the Ochr-y-cefn–Groes–Cefn–Llanrhaidr–Denbigh–Flint–Leeswood, Soughton, Gwaynynog, Gwespyr, Hawarden Nercwys, Neston–Great Ewloe–Thurstaston, Wrexham, Alyn Valley and Vale of Clwyd faults, and the Minera fault belt.

The Llanegryn (Mochras) Fault represents a significant Mesozoic to Cenozoic growth fault, downthrown on its western side. The fault juxtaposes Cambrian rocks at the surface and Oligocene rocks as proved at a depth of approximately 70 m below the surface in the Mochras Borehole. The throw is estimated to be in excess of 2000 m but is not known in detail as a BGS stratigraphical borehole sunk at Mochras Farm failed to penetrate the full succession (Woodland, 1971; Allen and Jackson, 1985). The fault was recognised from previous gravity and seismic studies (Allen and Jackson, 1985).

The Trawsfynydd and Craiglaseithin faults form a subparallel pair of fractures that transect Cambrian strata along the eastern flank of the Harlech dome. Both faults are only known from surface mapping, but lie within a marked north-trending topographical depression. The Trawsfynydd Fault is estimated to be downthrown to the east by approximately 1200 m. The Craiglaseithin Fault is mapped with a downthrow to the west, however there are no reported estimates of the amount of displacement (Allen and Jackson, 1985). It has been proposed that these faults were active during the Cambrian prior to the onset of volcanism (Allen and Jackson, 1985); indeed, other studies have suggested that they represent reactivated Precambrian faults that controlled patterns of Cambrian deposition and the localisation of subsequent Ordovician volcanism (e.g. Kokelaar, 1988; Howells et al., 1991).

The Cwm Pennant and Glaslyn–Nantmoor fractures extend north-east from the Llŷn Peninsula, transecting Ordovician strata in the central Snowdonia area. These comprise a zone of *en échelon* and anastomosing faults, of which the Glaslyn Fault may be linked to the Llanegryn Fault (Howells and Smith, 1997). A component of dextral, transcurrent displacement of up to 4 km is inferred for both fracture zones. Vertical downthrow of up to 1500 m is also inferred between the two faults (Howells and Smith, 1997).

Further to the east, the Conwy Valley–Soflen Fault runs approximately north-north-west and is mapped as coincident with the Conwy valley itself. It downthrows late Silurian strata to the east against the mid Ordovician strata of the Snowdon massif to the west. The vertical displacement is estimated to be in excess of 1800 m (Warren et al., 1984).

In the north-east of the region, the north-north-west-trending Vale of Clwyd Fault marks the eastern, fault-bounded margin of the Vale of Clwyd half-graben, where rocks of Permo-Triassic age are juxtaposed against Silurian strata of the Clwydian Range to the east and rocks of Carboniferous age to the west. In common with other half-graben in the East Irish Sea region, it controlled and confined Permo-Triassic deposition, which is estimated to range between 525 and 3500 m (Jackson et al., 1995; Davies et al., 2004). A series of *en échelon*, normal faults that transect the basin include the Denbigh, Gwaynynog, Cefn and Llanrhaidr faults, while similarly oriented faults include the Groes and Ochr-y-Cefn faults, which transect older, early Palaeozoic strata to the west. Of these, the Cefn Fault downthrows to the east and juxtaposes late Carboniferous strata with Carboniferous limestone, with a maximum throw estimated at 220 m, declining toward its southern termination in the early Palaeozoic crop (Warren et al., 1984). The Denbigh Fault downthrows to the east and juxtaposes Triassic and late Carboniferous strata and has a maximum throw estimated to be around 350 m (Warren et al., 1984). The Gwaynynog Fault form a pronounced landscape feature and downthrows to the east with a maximum throw estimated at 380 m (Warren et al., 1984). The Llanrhaidr Fault downthrows to the east and is estimated to have a maximum displacement of around 120 m.

5.3.5 Anglesey and the Menai Strait fault system

The Anglesey and Menai Strait fault system encompasses the region in the far north-west of Wales and is dominated by a largely subparallel plexus of north-east to south-west faults, which juxtapose Precambrian and early Palaeozoic rocks as well as late Palaeozoic strata (Howells, 2007). Although discussed widely in the scientific literature, there are no modern BGS publications that describe these structures with the exception of the Aberdaron and Pwllheli districts at the western end of the Llŷn Peninsula (Gibbons and McCarroll, 1993; Young et al., 2002). On the western end of the Llŷn Peninsula, the Llŷn shear zone comprises a zone of subvertical, mylonitic rocks and coincident faults such as the Daron Fault that juxtapose the undated megabreccia of the Gwna Group against late Neoproterozoic, intrusive igneous rocks and is often considered contiguous with strands of the Menai Strait fault system (Gibbons and McCarroll, 1993). The south-eastern named segment of the Menai Strait fault system is the Aber Dinlle Fault. This juxtaposes mid Ordovician strata against late Neoproterozoic strata with a relative downthrow to the north-west. There are no published estimates of the amount of displacement on the Aber Dinlle Fault.

The Dinorwic Fault is situated roughly beneath the Menai Straits and locally juxtaposes Carboniferous limestone against late Neoproterozoic rocks with the relative downthrow toward the north-west. There are no published estimates of relative downthrow on the Dinorwic Fault, although, along with the Aber Dinlle Fault, it has been implicated in controlling the distribution of late Neoproterozoic volcanic and sedimentary facies (Reedman et al., 1984). The Berw Fault is the north-westernmost fault of the Menai Strait system and locally juxtaposes Carboniferous limestone against late Neoproterozoic to early Palaeozoic metamorphic rocks, with an apparent downthrow on its northern side. This structure is characterised by subvertical fault rocks exposed at the surface, but is interpreted to control the development of a Carboniferous half-graben, although it also separates fundamentally different basement units and is likely to have had a long history of movement (Gibbons, 1987).

The Carmel Head Thrust in the north of Anglesey dips moderately toward the north and is exposed along the north Anglesey coastline. It has an apparent reverse sense of movement, translating Cambrian, metamorphosed basement rocks of the Monian Supergroup southward over Ordovician strata. The amount of displacement is unknown in detail but was estimated to be as much as 20 km (Greenly, 1919).

5.4 FOLDING

The principal major folds in Wales are developed in early Palaeozoic and older strata and were formed during Acadian shortening. These have an approximately 25 km wavelength and comprise the antiformal Harlech and Berwyn domes of North Wales and the intervening Llanderfal Syncline (Figure 27). To the north lies the Snowdon Syncline and Padarn Ridge Anticline (Figure 27) lying within the Menai Strait fault system. In central Wales, these are the Central Wales Syncline and adjacent Tywi Anticline (Figure 27). Major folds are typically strongly faulted and locally preserve verging, minor structures on their flanks. They have approximately upright axial planes with curvilinear hinge traces forming periclinal outcrop patterns, or locally more dome shaped, as in the case of the Berwyn dome of North Wales (Howells, 2007).

Subordinate folds of 5–10 km wavelength are less common; examples of these include structures such as the Rhiwnant Anticline, developed between on the western flank of the Tywi Anticline, and the Twyrch Anticline around Llanidloes (Davies et al., 1997).

Minor, metre to tens of metres-scale folds are widely developed, although their distribution is largely controlled by lithology. For instance, in some of the mudstone-dominated successions, minor folds are not observed, while in some of the multilayer successions, in particular interbedded turbidite mudstones and sandstones that are exposed at surface in the hinge zone of the Central Wales Syncline, abundant metre to tens of metres-wavelength, parasitic folds are developed. On the south-western limb, these verge toward the Tywi Anticline and are typically closed and more or less upright, with steeply inclined fold axial planes and short fold limbs that are often overturned. The overall style is similar on the north-west limb, with the opposing sense of vergence (Davies et al., 1997). In contrast, minor folds within the Tywi Anticline are typically moderately to steeply plunging and tighter, while the latest Silurian to Early Devonian strata form a monoclinal, synformal structure with a subvertical north-west limb within the fault zone. In North Wales, patterns of vergence for minor folds around the more dome-shaped major structures are typically more complex (e.g. Howells and Smith, 1997). Exposures of Cambrian and older basement rocks on Anglesey locally preserve complex patterns of fold superpositioning on a variety of scales (Treagus et al., 2003).

In South Wales, the South Wales Coalfield Syncline and adjacent Usk Anticline (Figure 27) comprise the main Variscan fold structure lying to the north of the Variscan fault and fold belt. The Variscan fault and fold belt (Figure 27) is an approximately east–west-trending, open pericline that passes westward into a series of tighter structures that are closely associated with Variscan thrust faults (Hancock et al., 1983).

5.5 UNCERTAINTY

Faults in Wales are not constrained by seismic investigation and are largely known from surface geological mapping of varying vintage, ranging from around 1900 to the present day. A fault is recognised as being present because distinctive units of strata are offset by varying amounts relative to one another, both horizontally and vertically (throw), and in a normal or reverse sense. Surface evidence is based on geological mapping, where faults may be seen at crop, or their presence, attitude and location may be ascertained from mapping offset formational boundaries, for which the degree of confidence is in turn dependent upon the nature and degree of confidence in mapping those adjacent formations at crop. It is important to understand the nature of geological faults, and the uncertainties which attend their mapped position at the surface. Faults are planes of movement along which adjacent blocks of rock strata have moved relative to each other. They commonly consist of zones, perhaps up to several tens of metres wide, containing several to many fractures. The portrayal of such faults as a single line on the geological map is therefore a generalisation.

Across much of Wales there is limited or no subsurface data, hence the faults described carry a high degree of uncertainty in terms of the presence, location and nature of subsurface structures.

6 Screening topic 3: groundwater

6.1 OVERVIEW OF APPROACH

This section explains what is known of shallow and deep groundwater flow regimes in Wales, 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 Wales 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 WALES

There is almost no information related to groundwater in the depth range of interest, i.e. between 200 and 1000 m, in Wales. There is some hydrogeological information related to areas where the Carboniferous Limestone Supergroup and the Permo-Triassic sandstone principal aquifers are present and other areas where relatively shallow groundwater is locally exploited for resources, typically to depths of a few tens of meters (Allen et al., 1997; Jones et al., 2000; Griffiths et al., 2002; Robins and Davies, 2016). 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 (RWM, 2015).

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The regional groundwater flow systems in Wales are conceptualised as being controlled by the broad distribution of geological units and the regional geological structure; the hydrogeological characteristics of those units; topography and the distribution of recharge, and other hydraulic boundary conditions, such as the coastline with the Irish Sea and the Bristol Channel.

The GVS for Wales (Table 3) divides rock units into three lithostratigraphical systems: basement rocks; Triassic to Devonian sedimentary cover, and a younger sedimentary cover sequence of Neogene to Jurassic sediments. These lithostratigraphical systems have a broad distribution across Wales (Figure 4) with large parts of the north-west (including Anglesey and the mountains of Snowdonia) as well as Mid Wales (bounded to the west by the Cambrian Mountains and south by the Brecon Beacons) underlain by units from the Silurian to Proterozoic basement rocks. Devonian, Carboniferous and Permo-Triassic sedimentary rocks underlie the South Wales valleys that drain to the south and south-west onto the low-lying coastal areas including Newport, Cardiff and Swansea. They also underlie large northerly draining river valleys such as the Clwyd and Dee in the north-east of the region. They include the only principal aquifers in Wales (the Mercia Mudstone Group marginal facies, the Permo-Triassic sandstones, and the Carboniferous Limestone Supergroup).

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

- the Carboniferous and younger sedimentary cover sequence
- the relatively low-permeability Precambrian and early Palaeozoic rocks that underlie large parts of northern, central and western Wales.

The latter system is characterised in the near surface by shallow, short groundwater flow paths and uncertain, and by analogy greatly, reduced permeability at depth.

Rocks from both these systems are found in the depth interval of interest across Wales, but there is a paucity of groundwater information, particularly related to flow, in the depth range of interest. For example, there are no boreholes extending >100 m bgl from which hydrogeological information can be obtained and there is no knowledge of offshore, submarine groundwater discharge, which could be an important pathway for discharge from karstic Carboniferous Limestone Supergroup aquifers in coastal and/or estuarine settings. The deep structure of the aquifers is poorly understood, as is their role in deep regional groundwater flow. The effect of faults as barriers to, or pathways for, groundwater flow is also very poorly known. Even in the depth interval of active groundwater exploitation hydrogeological information is limited. This is due to the relative importance of surface water for public supply, given the limited occurrence of principal aquifers, and because other aquifers, which cover the majority of Wales’s land area, are less important for public water supply. This lack of data can result in uncertainties for hydrogeological investigations (Robins and Davies, 2016) and in particular there is very limited information about potential pathways for groundwater movement from depth and between different groundwater systems.

Regional-scale structures (Section 2) and anthropogenic features (e.g. boreholes and mines) (Section 8) may provide potential pathways. For example, extensive mine working across parts of the region in Coal Measures have influenced water tables locally and have also allowed hydraulic contact between previously separated units. These potential pathways for groundwater movement between units and groundwater systems are discussed after a description of each of the groundwater systems.

6.3.1 Hydrogeology of the Carboniferous and younger sedimentary cover rocks

6.3.1.1 TRIASSIC MUDSTONES

The Triassic mudstones occur along the south-east Wales coastline. Despite the large populations in these areas, there are very few abstractions from the mudstone, and it is considered to be a poor aquifer. As a result, there are limited hydrogeological physical properties data for this formation. The stratum is a massive calcareous or dolomitic mudstone with evaporites and sparse limestones and sandstones (Waters and Laurence, 1987). The dominant mudstone restricts groundwater movement to faults, fractures and sandstone or siltstone units. Although a poor aquifer, the basal Mercia Mudstone marginal facies, where present, can act in hydrogeological continuity with underlying principal aquifers (Waters and Lawrence, 1987; Jones et al., 2000).

6.3.1.2 MERCIA MUDSTONE GROUP MARGINAL FACIES

The Triassic Mercia Mudstone Group marginal facies occurs in much smaller areas when compared to the two main principal aquifers, the Permo-Triassic sandstones and the Carboniferous Limestone Supergroup. For the purpose of this assessment, the Mercia Mudstone Group marginal facies has been classified as a principal aquifer, although key references to this unit (e.g. Jones et al., 2000) classify it as a secondary aquifer in Wales. The reason for its change in status is that, when it occurs directly upon the Carboniferous

Limestone Supergroup principal aquifer, mainly in areas of South Wales, it is expected to be in hydraulic continuity (Waters and Laurence, 1987; Jones et al., 2000).

The geographical extent of the Mercia Mudstone marginal facies is small: it occurs in areas of South Wales, and the recharge area and thus resource are limited (BGS, 1986). There are very few hydrogeological aquifer properties data for the marginal facies in South Wales, although yields from boreholes (now all decommissioned) in Cardiff are reported to be highly variable, ranging from dry to 1900 m^3/d achieved from a 30 m-deep, 200 mm-wide borehole at ST 145 699 (BGS, 1986; Jones et al., 2000).

6.3.1.3 SHERWOOD SANDSTONE GROUP

The Permo-Triassic Sherwood Sandstone Group principal aquifer is the most important aquifer in North Wales (Allen et al., 1997), providing water for public supply, industry and agriculture. The Sherwood Sandstone Group occurs in the fault-bounded Vale of Clwyd basin, where its western boundary is marked by the Denbigh Fault, which is downthrown to the east by the by about 1500 m (Allen et al., 1997), whilst the Vale of Clwyd Fault determines the eastern boundary (Warren et al., 1984).

The Vale of Clwyd is subdivided into two distinct structural basins, separated by the Gwaynynog Fault, interpreted as a near-vertical, normal fault (Warren et al., 1984) dividing the Rhyl sub-basin in the north and the larger Ruthin sub-basin to the south (Wilson et al., 2002). The faults bring the Sherwood Sandstone Group into contact with Silurian and Carboniferous strata (Allen et al., 1997), but groundwater outflow into these less permeable strata is not thought to be significant (Water Resources Board, 1973).

Groundwater storage and flow within the Sherwood Sandstone Group is dominated by the lithologically controlled intergranular (primary) porosity and permeability, which can be locally influenced by faulting and fracturing (Allen et al., 1997). The intergranular porosity is controlled by the degree of cementation of the sandstones (Allen et al., 1997; Griffiths et al., 2002). Dissolution of evaporite cements, notably anhydrite in the Sherwood Sandstone Group, has created most of the primary porosity (Griffiths et al., 2002). Pumping-test data show that hydraulic conductivity can be spatially variable, being highest within the clean, well-sorted sands and less in more well-cemented horizons (Allen et al., 1997).

In the Vale of Clwyd, localised fissures associated with faulting can influence groundwater flow within the Sherwood Sandstone Group aquifer (Reeves et al., 1975). Geophysical logging techniques within a 91.4 m-deep borehole (Water Resources Board, 1973) identified a single fissure at 58 m depth that contributed 80 per cent of the flow into the borehole (Reeves et al., 1975; Allen et al., 1997). Unproductive b are rare in this aquifer and sustainable yields up to 500 l/s are possible from large diameter boreholes (BGS, 1989).

Sampling of water-supply boreholes in the Vale of Clwyd shows that groundwater chemistry from the Sherwood Sandstone Group is generally hard but of low salinity. Saline groundwater can occur within the Sherwood Sandstone Group in some places; the source is likely derived from halite dissolution rather than seawater (Griffiths et al., 2002).

6.3.1.4 CARBONIFEROUS LIMESTONE SUPERGROUP

The Carboniferous Limestone Supergroup is an important principal aquifer in Wales for public, industrial and agricultural water supply. It occurs in several distinct areas across Wales, from Anglesey and the Vale of Clwyd in the north, to Pembrokeshire, Gower, the periphery of the South Wales coalfield and between Chepstow and Penhow in the south. However, attempts to drill boreholes for water supply in the limestone have not always been successful due to the heterogeneous nature of the bedrock.

The limestones within this group are susceptible to both localised and landscape-scale karstic development and this is prevalent across most of the crop. The Carboniferous Limestone Supergroup aquifers are best characterised where they occur along the periphery of the South Wales coalfield, forming classic areas of upland karst including doline fields, losing and gaining rivers, limestone pavements and cave systems (Crowther, 1989; Waltham et al., 1997). The Carboniferous Limestone Supergroup exhibits varying degrees of karstification in Wales, with extensive cave formations in South Wales. In contrast, there is relatively little karst formation where the limestone occurs in Anglesey, and, although it is classed as a principal aquifer, no groundwater investigations thus far have identified any areas capable of providing enough water for public supply (Environment Agency Wales, 2008g).

The matrix of the Carboniferous Limestone Supergroup typically has a low primary porosity (Allen et al., 1997; Robins and Davies, 2016). The secondary porosity, created by solution-enlarged fractures, bedding planes and conduits (Allen et al., 1997), is most important for the flow and storage of groundwater.

Groundwater level fluctuations can be as great as 40 m, as measured in a borehole at Tythegston, South Wales (SS 851 789), between 1976 and 1983 (BGS, 1986), confirming the low specific yield of the Carboniferous Limestone Supergroup aquifer in certain areas. Transmissivities range from 4 m^2/d to 5900 m^2/d at the Beacon Tower Borehole, Vale of Glamorgan, and the 'Milton' public water supply borehole, Pembrokeshire, respectively (Allen et al., 1997). In the latter, groundwater intercepts highly permeable karstic features and fault zones (Allen et al., 1997).

Faults, fissures and bedding planes have an important influence on groundwater flow within the Carboniferous Limestone Supergroup. They can act as either barriers, or conduits for groundwater (Clark and Aldous, 1987). Tracer tests are often used to determine connections within limestone aquifers and flow velocities that can be of the order of km/day (e.g. Allen et al., 1997; Hobbs, 2000).

Boreholes, springs and wells sampled for groundwater chemistry indicate groundwater is of Ca-HCO_3 type (Environment Agency Wales, 2008a–g). Examples of flow velocities, where bacteriophage and fluorescein tracers were injected into sinks and losing rivers within the Schwyll catchment near Bridgend, South Wales, produced peak-flow velocity values between 1500 m/day and 5200 m/day (Hobbs, 2000). Groundwater age dating using CFCs and SF_6 (Gooddy et al., 2006) suggests that the average age of groundwater in the Carboniferous Limestone Supergroup in Anglesey can range between two years to about 40 years (Environment Agency Wales, 2008g).

6.3.1.5 RAGLAN MUDSTONE FORMATION

The Raglan Mudstone Formation crops out across Mid and South Wales to Pembrokeshire and consists of red mudstones and siltstones with sporadic fluvial sandstones and abundant calcretes (Jones et al., 2000). Groundwater flow and storage within the formation is limited to joint and fault-related fracture systems (secondary porosity), which reduce in frequency with depth (Moreau et al., 2004). The effective aquifer saturated thickness is considered to be 40 m based on the analysis of pumping test and drilling data compiled by the Environment Agency (now Natural Resources Wales) (Jones et al., 2000). The permeability of this formation is limited within the mudstone, resulting in variable yields.

Groundwater chemistry within the Devonian Old Red Sandstone, which includes the Raglan Mudstone Formation, suggests that shallow groundwater chemistry is of Ca-HCO_3 type. However, some groundwater can be saline or Na-HCO_3 type (Moreau et al., 2004). Brackish and saline groundwater has been encountered in boreholes in Devonian strata from both Wales and the Welsh Borders, especially where the aquifer is confined (Moreau et al., 2004).

6.3.2 Hydrogeology of the Precambrian and early Palaeozoic rocks

Precambrian and early Palaeozoic rocks underlie a large area of Wales and comprise mudstones, siltstones and sandstones, with metamorphic, volcanoclastic and igneous rocks. Groundwater flow is controlled by secondary permeability within fractures, faults and the near-surface weathered zone. The occurrence and interconnection of these pathways decreases with depth, as does the scope for groundwater movement. Shallow wells and springs can be numerous (Robins and McKenzie, 2005). Groundwater studies in an upland catchment (Plynlimon) using a network of 11 shallow boreholes up to 15 m depth and three up to 50 m depth indicate that groundwater levels are often close to the surface in early Palaeozoic aquifers (Neal et al., 1997) and that fracture flow is the dominant pathway for groundwater (Neal et al., 1997). The study also highlights that the fractured nature of the early Palaeozoic strata is sufficient to contain widespread groundwater to depths of 30 m bgl that are 'important for sustaining water supplies for small communities' (Neal et al., 1997).

Analysis of groundwater samples collected from the Silurian–Ordovician strata show that acidic groundwater of Na-Cl-(SO_4) type occurs in the shallower sites. At greater depth (i.e. from 20–50 m), more mineralised groundwater of Ca-HCO_3 type is more likely (Shand et al., 2005).

Groundwater temperatures vary between 4 and 12°C measured from water supply boreholes in the Teifi catchment, ranging in depth from five to approximately 100 m, and between 6 and 12°C in boreholes 1.5–50 m deep in the Plynlimon catchment (Shand et al., 2005). In the Teifi catchment, the lower temperatures reflect 'very shallow flow', and 'typical temperatures are 8–11°C' (Shand et al., 2005).

In the upper Severn and Wye catchments, groundwater analysed for CFCs and SF_6 suggests recharge ages ranging from several months to 10 years in shallow boreholes (up to 26 m depth) and up to 45 years in deeper boreholes (up to 100 m) (Shand et al., 2005). Analysis of water from two springs and one 40 m-deep borehole in the Precambrian Gwna Group, Anglesey, confirmed that both springs had a large component of 'modern' groundwater, defined as groundwater that has concentrations at or above modern atmospheric concentrations (Gooddy et al., 2006). Groundwater from a 40 m borehole abstracting drinking water from the Gwna Group was dated at 20 years old (Environment Agency Wales, 2007). CFC and SF_6 age dating of groundwater samples obtained from boreholes and springs indicates that groundwater within the PRTIs in Wales is mostly <50 years old (Environment Agency Wales, 2007: Shand et al., 2005).

In certain settings, such as at the mineral (saline) springs of Builth Wells and Llandrindod Wells, with maximum salinities of 16 380 and 5340 mg/l respectively (Edmunds et al., 1998), geochemical evidence suggests the age of the spring water can be as great as 1–2000 and 8200 years BP respectively (Edmunds et al., 1998).^{14}C data (Darling et al., 1997) further support the theory that groundwater residence times of thousands of years are possible in the Palaeozoic aquifers. Despite the high salinity and evidence for long residence times, the springs at Builth and Llandrindod Wells display temperatures between 11 and 13°C. In addition, the total discharge from the springs is very low (combined 2 l/s (Edmunds et al., 1998)). Edmunds et al. (1998) states that 'the most likely origin for these waters is the deep circulation of meteoric water over a residence time of several thousand years, which has risen slowly along minor fracture systems'.

6.4 EVIDENCE FOR CONNECTIONS BETWEEN GROUNDWATER SYSTEMS

6.4.1 Geological pathways

6.4.1.1 THERMAL SPRINGS

Taffs Well is the only known thermal spring in Wales and is shown on Figure 33. The spring, located on the southern limb of the South Wales Coalfield Syncline, has a stable temperature of 21.6°C ± 0.5 (Farr and Bottrell, 2013), only varying for periods of several hours in response to back flooding from the adjacent River Taff. Limited mixing with surface waters can occur when the adjacent River Taff is in flood. Spot gauging indicates the outflow is about 5 l/s. It is inferred from noble gas data that recharge occurs at 500 m above OD (Burgess et al., 1980; Farr and Bottrell, 2013) and that groundwater flow occurs below the South Wales Coalfield Syncline. Strontium isotope data suggest interaction of the groundwater with the sandstones of the Carboniferous Marros Group (previously the Millstone Grit) and the underlying Carboniferous Limestone Supergroup. The depth of groundwater flow is estimated at least 400 m bgl (Farr and Bottrell, 2013).

In other areas where thermal springs are associated with basinal structures such as in Bath, Derbyshire, Bristol and the Republic of Ireland, there can be multiple thermal springs (>15°C). In Wales there is little evidence of this, although more research on saline springs or at the margins of basinal structures such as the South Wales coalfield may provide more evidence of deep groundwater flow.

6.4.1.2 DEEP (>200 M) GROUNDWATER TEMPERATURE

The majority of deeper groundwater temperature data are located within the more populous South Wales region. The Devonian and Carboniferous rocks that form the South Wales Coalfield Syncline were part of a series of surveys of groundwater temperature and chemistry, undertaken across England and Wales (Burley and Gale, 1981). Measured geothermal gradients in the South Wales coalfield were shown to vary between 20 and 25°C/km (Thomas et al., 1983). Busby et al. (2011) estimates temperatures across the UK at intervals of 100, 200, 500 and 1000 m bgl, suggesting that groundwater temperatures in South Wales would be <24°C at 500 m. This relatively low geothermal gradient could be a result of minewater rebound and mixing with shallow modern waters within the measured boreholes or shafts, however, the paucity of deep temperature data should also be noted. Farr et al. (2016) also confirms that the measured geothermal gradients within the coalfield can show significant variation, from 13.9 to 32.8°C/km, averaging 23.9°C/km with temperatures at 1000 m depth ranging from 22°C to 42°C (Farr et al., 2016). However, the controls for the variability of geothermal gradients within the coalfield are poorly understood.

Elsewhere across Wales there are limited opportunities to measure groundwater temperatures at depths >200 m.

6.4.2 Anthropogenic pathways

There are numerous deep boreholes (Section 8.10, Figure 34) in the south and north-east Wales coalfield areas drilled during the evaluation of the coal resources. In these areas the maximum concentration of deep boreholes is seven per 1 km^2. On Anglesey, at Parys Mountain, there is a cluster of deep boreholes drilled to evaluate the lead/zinc/copper deposit, including one area where there are 60 deep boreholes drilled in 1 km^2.

The most significant pathways for groundwater flow between deep and shallow groundwater systems are abandoned and interconnected mine shafts and galleries that can facilitate groundwater movement to hundreds of metres depth. These are most common in the mined areas of Wales, namely the coalfields in South and north-east Wales and metal mining areas of Mid and North Wales (Section 8). Many of the deep mine shafts have been sealed for safety and very few deep boreholes or shafts remain open.

BGS datasets show the spatial distribution of anthropogenic features (coal and metal mines) that occur below 100 m NGS datum. Many coal and metal mines in Wales were actively dewatered during operation. Drainage adits are designed to provide gravity-driven pathways for mine water and groundwater and are abundant across mined areas, frequently draining towards the natural hydrological discharge points or topographically low points, including river systems or the coast. Perhaps the best-known example in Wales is the Milwr–Halkyn drainage adit in north-east Wales. It was built to dewater lead mines within the Carboniferous Limestone Supergroup (principal aquifer) from Loggerheads to Bagillt and its drainage is of the order of 55 000 m^3/d (Robins and Davies, 2016). Once extraction of materials stopped, dewatering ceased and minewater rebound occurred. The rebounding water flooded abandoned workings, with the knock-on effect of minewater breakouts. These were often in natural discharge areas, such as the edges of river banks (Robins et al., 2008).

In the South Wales coalfield, results from groundwater flow modelling have suggested that minewater transport is limited to the catchment and subcatchment scale and that there is little regional transport of groundwater (Robins et al., 2008).

The mean annual temperatures of 16 minewater adits, measured over the period of one year in the South Wales coalfield, varied from 10.3°C to 18.6°C with an overall mean of 13.3°C (Farr et al., 2016). The majority of the measured minewater discharge temperatures were above the mean annual air temperature, suggesting that in many areas, mine water can ascend to the surface from depths of several hundreds of metres via gravity-driven adits. Based on measurements at 62 minewater sites (mainly adits) The Coal Authority estimates that over 2000 l/s drain from abandoned mines in the South Wales coalfield (Farr et al., 2016).

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

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

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

7.2 GLACIATION

7.2.1 A UK-scale context

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

It is clear from the recent geological record that glaciers have been repeatedly active within the UK landscape over the past two and half million years (Clark et al., 2004; Lee et al., 2011). Numerous periods of glaciation have been recognised, although the scale and extent of glaciers have varied considerably. Most glaciations have been comparatively small (i.e. highland glaciations), although some have been more extensive with glaciers expanding into lowland parts of the UK, i.e. lowland glaciations (Clark et al., 2004; Lee et al., 2011). Over the past half a million years, at least two continental-scale glaciations have affected the UK with ice sheets covering parts of lowland UK, on one occasion as far south as the London area (Figure 28: RWM 2016a; Clark et al., 2004; Loutre and Berger 2000).

Whether glaciations will specifically affect the UK over the next one million years is open to conjecture (Loutre and Berger, 2000). This is because the impacts of global warming and the current melting of the Greenland Ice Sheet on the long-term climate system are poorly understood, although the general scientific consensus is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions means that their occurrence cannot be discounted.

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

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

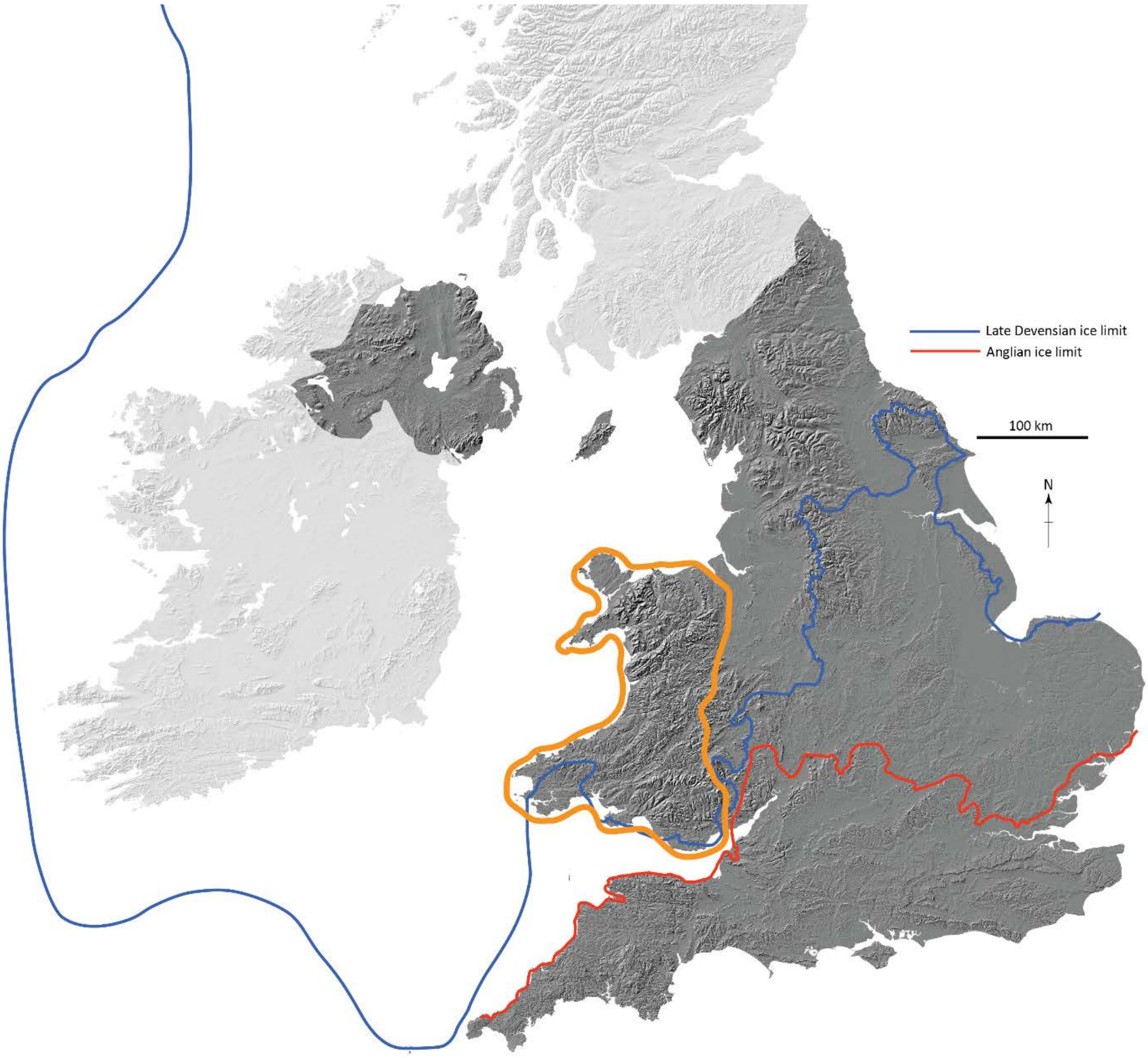

Figure 28 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (about 480 to 430 ka) and late Devensian (about 30 to 16 ka). The location of Wales is delineated by the orange line. Produced using Copernicus data and information funded by the European Union — EU-DEM layers ©EEA.

7.2.2 A regional perspective

Based upon geological evidence it is widely accepted that Wales has been glaciated repeatedly during the past two and a half million years (Quaternary Period: RWM 2016a; Clark et al., 2004). The last known highland glaciation, which was restricted to some highland areas of Wales, ended just over 11 000 years ago during a time interval called the Younger Dryas (RWM, 2016a). During the preceding glaciation, known as the late Devensian (about 29 000–15 000 years ago), several ice caps formed over highland areas of Wales and coalesced to form a major sector of the last British–Irish ice sheet (Clark et al., 2012). This glaciation extended over much of northern and central UK and was the second of two known continental-scale glaciations to affect the UK (Clark et al., 2004). Direct evidence for earlier glaciations in Wales, including the Anglian continental-scale glaciation, was largely eroded during the late Devensian glaciation. However, the elevation of its highland source areas and the position of Wales relative to a prominent North Atlantic moisture source (the Gulf Stream) made it highly susceptible to being glaciated.

Over the next million years, assuming Britain is glaciated, it is likely that Wales will experience highland glaciation and potentially lowland and continental glaciation (RWM, 2016b). This is because the elevation of its highland source areas and the position of Wales relative to the Gulf Stream make it highly susceptible to glacier inception. During all scales of glaciation, glacial overdeepening of valleys in highland areas may, over multiple glacial cycles, cause the localised lowering of the ground surface into the very top of the depth range of interest (French, 2007) , specifically in pre-existing valley areas. The formation of meltwater-incised valleys beneath glaciers (tunnel valleys) in lowland areas of Wales adjacent to the margins of larger-scale lowland and continental glaciations may also result in the localised lowering of the ground surface into the very top of the depth range of interest (French, 2007). Collectively, overdeepening of glacial valleys and the formation of tunnel valleys can lead to the development of highly localised groundwater behaviour and chemistry (French, 2007). Wales may be affected by isostatic rebound and/or a glacier forebulge during a lowland or continental glaciation which affects either an adjacent onshore 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 (French, 2007). The extensive coastline of Wales makes coastal areas susceptible to saline groundwater incursion due either to global sea-level change (driven by global patterns of glaciation) or regional isostasy (French, 2007). Saline groundwater incursion may alter the temporal and spatial patterns of groundwater behaviour (French, 2007).

7.3 PERMAFROST

7.3.1 A UK-scale context

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

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

7.3.2 A regional perspective

Under future cold climates over the next million years, it is likely that Wales will be subjected to the development of permafrost to a depth of a few hundred metres (Shaw et al., 2012; RWM, 2016b). 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 29). 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 29).

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).

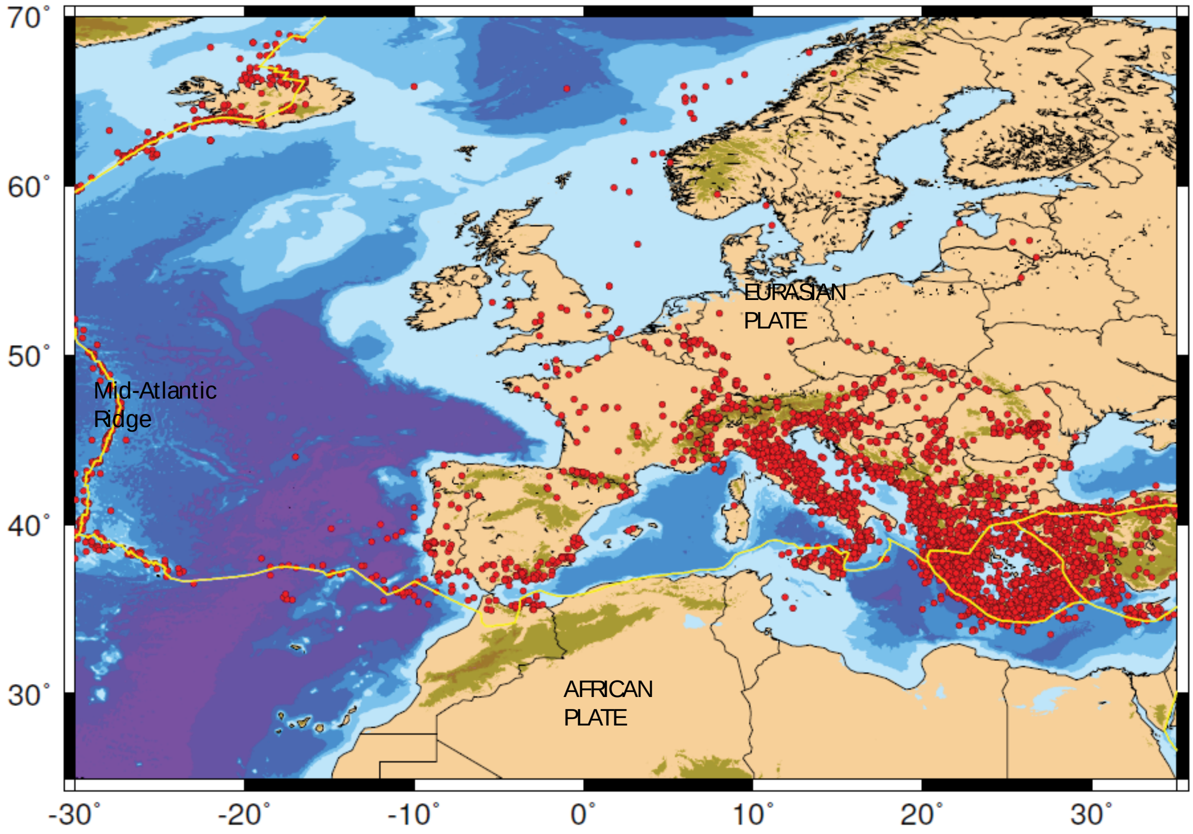

Figure 29 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated 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 (between magnitude 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 30 shows a map of all of the main shocks in the catalogue. The symbols are scaled by magnitude (Mw). It is worth noting that the location uncertainty is ±5 km for instrumental earthquakes and up to ±30 km for historical earthquakes (Musson, 1994). An analysis of the British seismicity clearly shows that it is not correlated with the major tectonic structures that bound the tectonic terranes in the UK (Musson, 2007). The terranes are homogeneous in terms of crustal properties (e.g. distribution and style of faulting), but the seismicity within each block is heterogeneous (Musson, 2007). There are spatial variations in the level of seismic activity across the UK. Western Scotland, western England, Wales, south-western Cornwall and the area off the coast of the south-eastern England are the areas of highest activity. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free

It is generally observed that the geographical distribution of British seismicity of the modern instrumental period follows rather closely the same distribution as the historical record of the last 300 years. However, there are three significant exceptions to this: south-west Wales, the Dover Straits, and Inverness. In these areas there was an intense historical seismic activity (as shown by the squares in Figure 30), which does not correspond to an intense instrumental seismicity. The Dover Straits area is notable for having produced relatively major (≥5 Mw) earthquakes in historical times (the last in 1580) and very little since.

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

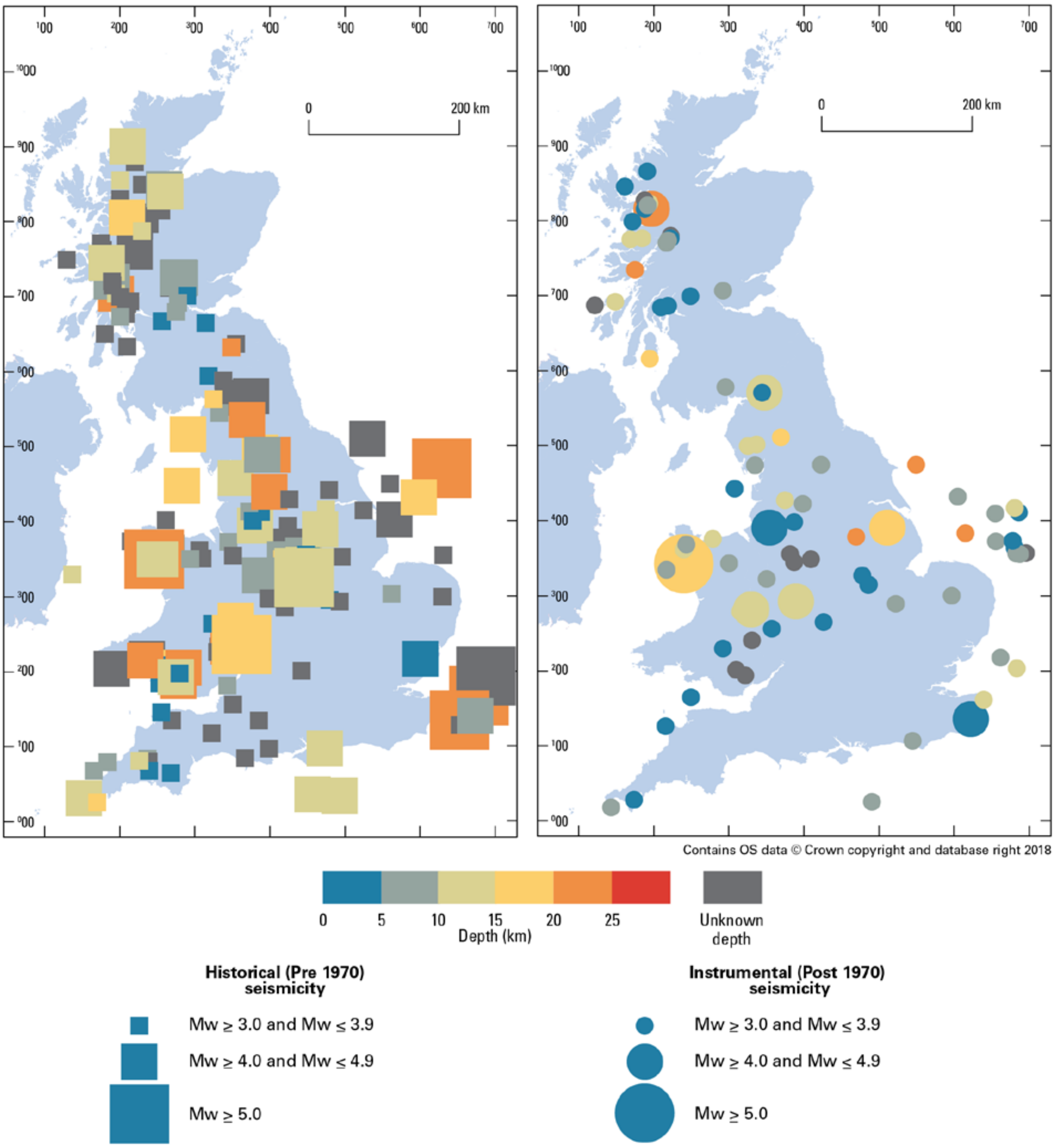

Figure 30 Distribution of the mains shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

7.4.1.2 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 31 shows the distribution of focal depths in the catalogue. These are distributed throughout the crust and the maximum depth in the catalogue is 28 km. This suggests that there is a relatively broad seismogenic zone, i.e. the range of depths in the lithosphere where earthquakes are generated. The larger earthquakes, e.g. the 7 June 1931 Mw 5.9 Dogger Bank earthquake and the 19 July 1984 Mw 5.1 Lleyn earthquake, tend to occur at greater depths. Earthquakes with magnitudes of around Mw 5 nucleating at depths of 10 km or greater will not result in ruptures that get close to the surface, since the rupture dimensions are only a few kilometres. Similarly, smaller earthquakes would need to nucleate at depths of less than approximately 1 km to get close to the surface. An earthquake with a magnitude of Mw 6.0 or above, nucleating at a depth of less than 10 km and with an upward propagating rupture, could, in theory, be capable of producing a rupture that propagates close the surface. In this case, the expected average rupture displacement could be 20 cm or greater.

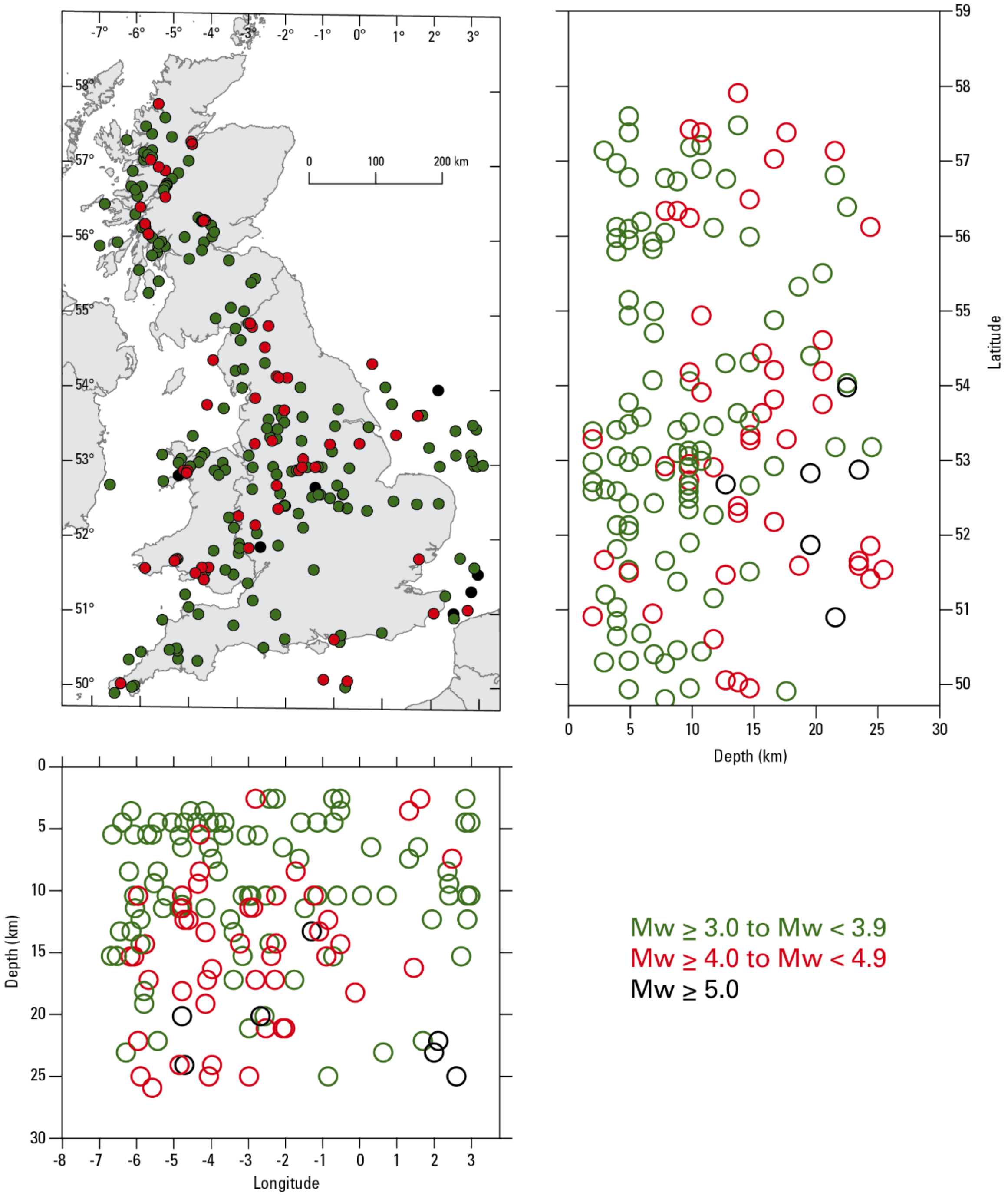

Figure 31 Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

7.4.1.3 Maximum magnitude (Mmax)

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

7.4.1.5 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

Figure 32 shows earthquake activity across Wales. North Wales is one of the most concentrated seismic areas in the mainland Britain, with a relatively high number of earthquakes with magnitudes of 4 Mw or greater for the UK. Most of these occurred on the Llŷn Peninsula, at the north-west edge of Snowdonia. The largest earthquake in this area was the 1984 Llŷn Peninsula earthquake (Turbitt et al., 1985), which had a magnitude of 5.1 Mw, and was felt over all of Wales, most of England and the east coast of Ireland. The epicentre was south-west of Caernarfon in the northern part of the Llŷn Peninsula. The focus for this earthquake was relatively deep, over 20 km (Trodd et al., 1985), which limited the amount of damage. However, some superficial damage was caused to chimneys and plaster as far away as Liverpool. The earthquake was followed by a notable after shock sequence of several hundred earthquakes (Marrow and Walker, 1988), the largest of which had a magnitude of 3.7 Mw. The Llŷn Peninsula experienced earthquakes with magnitudes of greater than 4 Mw in 1534 (4.2 Mw), 1690 (4.9 Mw), 1852 (5 Mw), 1903 (4.6 Mw) and 1940 (4.4 Mw). The epicentres for these events are close to the 1984 earthquake (Musson, 1994).

South Wales has also experienced damaging earthquakes (Musson, 2007). For example, the area around Swansea was struck by earthquakes in 1727 (4.9 Mw), 1775 (4.8 Mw), 1832 (4 Mw), 1868 (4.6 Mw) and 1906 (4.9 Mw). The 1906 earthquake brought down large numbers of chimneys and stonework, and also caused some injuries (Musson, 1994). It was also felt strongly in the mines of the South Wales coalfield and safety checks were carried out in some pits.

Further west, earthquakes with magnitudes of 4.8 Mw and 4.7 Mw occurred in Pembroke in 1892 and Carmarthen in 1893 (Figure 32). Their epicentres were very close in space and time, but their effects were different, suggesting a different radiation pattern. The Pembroke event was strongly felt in South Wales and little in North Wales, whereas, the effects of the Carmarthen event were much stronger in the north (Musson et al., 1984; Musson, 1994, 2007).

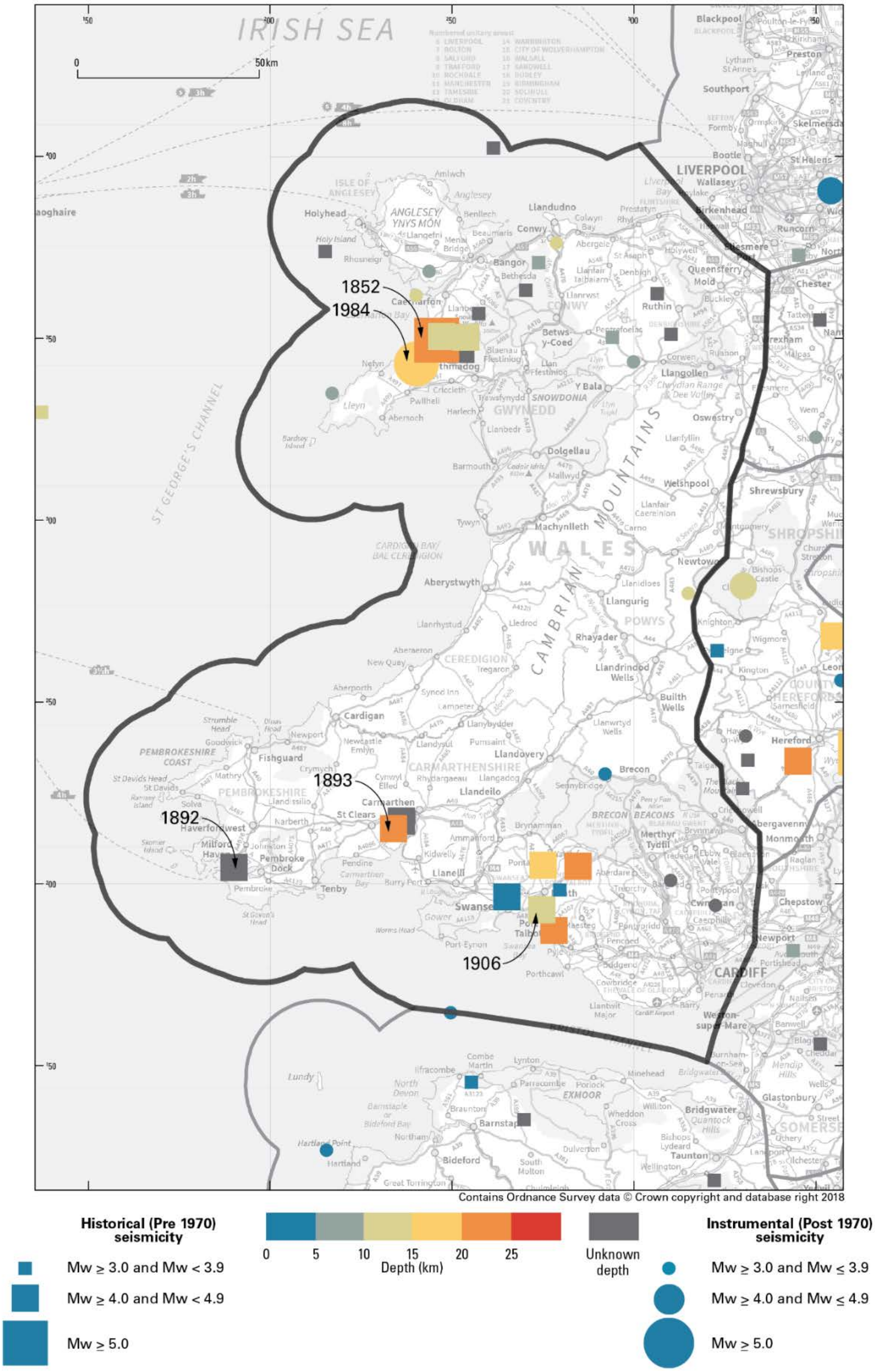

Figure 32 Historical and recorded earthquakes in Wales. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

This section explains what is known of mineral resources in Wales. 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.

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 WALES

The distribution of mineral resources in Wales is shown in Figure 33. Wales has large coalfields in the south and north-east that have been extensively mined for coal. There are a number of ferrous and non-ferrous metallic mineral deposits in Wales, some of which have been exploited in the past to depths of 100 m or more below NGS datum. Two metallic mineral deposits in North Wales may remain prospective. Wales has some potential for shale gas and oil in the coalfield areas. The East Irish Sea gas/oil fields lie just outside the 20 km buffer from the north coast.

8.3 COAL AND RELATED COMMODITIES

South and north-east Wales have large coalfields. Both have been extensively mined at depth.

The South Wales coalfield extends from near Pontypool in the east to south of Haverfordwest in Pembrokeshire. The coalfield was intensively worked from the late 19th century to the mid-20th century (some mining was potentially prehistoric; mining was systematic in Roman times, and more intensive from the Middle Ages). South Wales was formerly one of Britain's most productive coalfields and the principal source of coal exports. Peak production was achieved in 1913 when 57.9 million tonnes were mined from over 600 collieries. The number of collieries decreased to 329 in 1944 and 80 in 1967 before a rapid decline led to the closure of all deep-shaft mines at the time of privatisation of British Coal in 1994. Although considerable resources of coal remain, the South Wales coalfield is geologically complex and heavily faulted, which in part contributed towards its decline. Structurally, the coalfield is a broad, asymmetric, east–west-trending syncline. Structures are highly complex on the south and north-west outcrops, with much thrust faulting. Even in areas of relatively simple structure, the abundance of small-scale faults created problems for underground mechanised long-wall mining.

The North Wales coalfield occupies an area along the north-east margin of the region and comprises two smaller coalfields, the Flintshire coalfield and the Denbighshire coalfield. These coalfields dip generally to the east and as a result deep coal (over 100 m deep) is only present along the border with England around Queensferry and Wrexham, and possibly in the East Irish Sea. Because of the geological complexity of the coal in this area mines were generally small scale and rarely exceeded 150 m below NGS datum. The deepest mine did, however, reach depths of over 1000 m below NGS datum. The majority of deep mining ceased in the early twentieth century although mining continued until 1987. There is also a small, outlying coalfield on Anglesey that has been mined in the past. The last operating pit, Point Marquis Colliery, closed in the early 1880s.

Prior to its closure in 2008, coal mine methane was captured and utilised at Tower Mine in South Wales as a by-product of mining operations. There are no current licences for coalbed methane production or coal mine methane production in any of the coalfield areas. However, petroleum exploration and development licences (PEDL) have been granted around Wrexham, Bridgend, Neath Port Talbot, Swansea, Rhondda Cynon Taff and the Vale of Glamorgan. There are two licences for abandoned-mine methane production: one in the Bridgend area of South Wales and the other near Wrexham in north-east Wales.

There are currently two Coal Authority licences for underground coal gasification: one in the Loughor estuary and the other straddling the English and Welsh border off the Point of Ayr in the Dee estuary. Both are currently being investigated for their feasibility.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

There are no evaporite resources present onshore in Wales, however, there are considerable thicknesses of halite present in Cardigan Bay, the Bristol Channel and Central and East Irish Sea basins. 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

Slate has been extensively quarried underground in the Blaenau Ffestiniog area to depths of around 140 m below NGS datum. This area includes the Cwmorthin, Gloddfa Ganol and Llechwedd slate mines. Slate mining has occurred elsewhere in North Wales but at much shallower depths.

There are no other deposits of bedded or other miscellaneous deposits that have been worked deeper than 100 m below NGS datum in Wales. However, a number of commodities have been mined at shallow depths including manganese, refractory silica, limestone and pyrite.

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 location of veins. In most cases mine plans are not available or not accurate enough to delineate the surface expression of underground workings.

Iron ores have been mined to depths greater than 100 m below NGS datum in the Llanharry area, annotated on Figure 33 with the letter B, north-west of Cardiff. This extensive iron ore mine reached a maximum of 215 m below NGS datum and closed in 1971.

There are a number of non-ferrous metal orefields in Wales. Mineralisation is usually in the form of linear, subvertical veins infilling faults and fissures occurring in a variety of rocks of different geological ages and settings. The principal orefields (Figure 33) are:

- Cardiganshire and Montgomeryshire: lead, zinc
- Flintshire and Minera: lead, zinc
- Llanrwst: lead, zinc
- Snowdonia: copper, lead, zinc
- Dollgellau: gold, copper, lead

The smaller orefields (Figure 33) are:

- Llanbedr: manganese
- Parys Mountain: copper, lead, zinc
- Great Orme: copper
- Llanfair Talhaiarn: copper, lead, zinc

The areas listed contain most of the known non-ferrous metallic mineralisation in Wales. Large parts of each area are, however, not intensively mineralised and have not been extensively mined or mined to depths exceeding 100 m below NGS datum. Because of the widespread distribution of mineral veins and the extent of past shallow mine workings, 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 outside of the areas listed that have undergone historic mining. However, most of these mineral veins have not been extensively mined or mined to any great depth.

All areas of mining that are known or suspected to exceed depths of 100 m below NGS datum are shown on the map. The deepest metallic mineral mines in Wales, such as Talargoch, Esgaurmwyn and Minera, which extend to just over 300 m below NGS datum, are located in the lead and zinc orefields of north-east and Mid Wales.

Mining was extensive in many of the areas marked on Figure 33, reaching a peak in the mid-19th to mid-20th centuries, after which it gradually declined as a result of the high costs of working this style of mineralisation and competition from lower-cost producers overseas. The last mine to operate was Gwynfynydd, in the Dollgelleau gold belt, which closed in 1999. The most intensely mined area occurs in a north–south belt from just south of Mold to near Holywell in the north, where many deep mines are linked underground. These run along the line of the Milwr tunnel, a 16 km-long adit constructed to drain the mine workings, which is one of the longest such adits in the UK. Other deep metal workings in North and central Wales worked individual veins and are more isolated.

There are two known ore deposits (Parys Mountain and Coed-y-Brenin (Figure 33) that are currently or have recently been evaluated for their mineral potential. Both could be considered for exploitation in the future to depths that may exceed 100 m below NGS datum.

Parys Mountain was the world's largest copper mine in the latter part of the 18th century. More recently it has been evaluated for lead, zinc and copper ores that surround the old copper mine at depths of several hundred metres. This evaluation included the sinking of a shaft and trial mining. While currently uneconomic to extract, higher metal prices in the future could make mining of the ore viable.

Coed-y-Brenin is a small porphyry-copper deposit that was evaluated by drilling and sampling in the 1970s. It is within the Snowdonia National Park and is unlikely to be mined under current economic conditions.

8.7 HYDROCARBONS (OIL AND GAS)

There are no conventional hydrocarbon fields on or offshore in Wales, however, the East Irish Sea oil and gas fields form a line just outside the 20 km coastal buffer zone to the north of Rhyl. The small gas field recorded by OGA data north of Bridgend is a coalbed methane resource.

Areas of South and north-east Wales have been identified as being prospective for shale oil/gas to the south of the South Wales coalfield and to the north-east of the North Wales coalfields, relating to deeply buried, organic-rich Carboniferous rocks, however, no drilling has been undertaken to investigate these areas and no resources have yet been proved.

8.8 UNDERGROUND GAS STORAGE

There are no planned, under construction or operating underground gas storage (UGS) facilities in Wales. There seems little immediate prospect for UGS with any potential probably lying in lined or unlined hard rock locations, or offshore within thickened halite in the St George’s Channel basin, which lies within the 20 km zone being considered.

8.9 GEOTHERMAL ENERGY

There are no deep geothermal heating systems currently operating in Wales. There is little geothermal energy potential in Wales because of a lack of large granite intrusions or deep, porous, sedimentary basins.

Locally, there is potential for minor district heating schemes using ground sourced heat pumps in abandoned mine workings, particularly in the coalfield areas.

8.10 HIGH DENSITY OF DEEP BOREHOLES

There are numerous deep boreholes (Figure 34) in the south and north-east Wales coalfield areas drilled during the evaluation of the coal resources. In these areas the maximum concentration of deep boreholes is seven per 1 km^2.

On Anglesey, at Parys Mountain, there is a cluster of deep boreholes drilled to evaluate the lead/zinc/copper deposit, including one area where there are 60 deep boreholes drilled in 1 km^2.

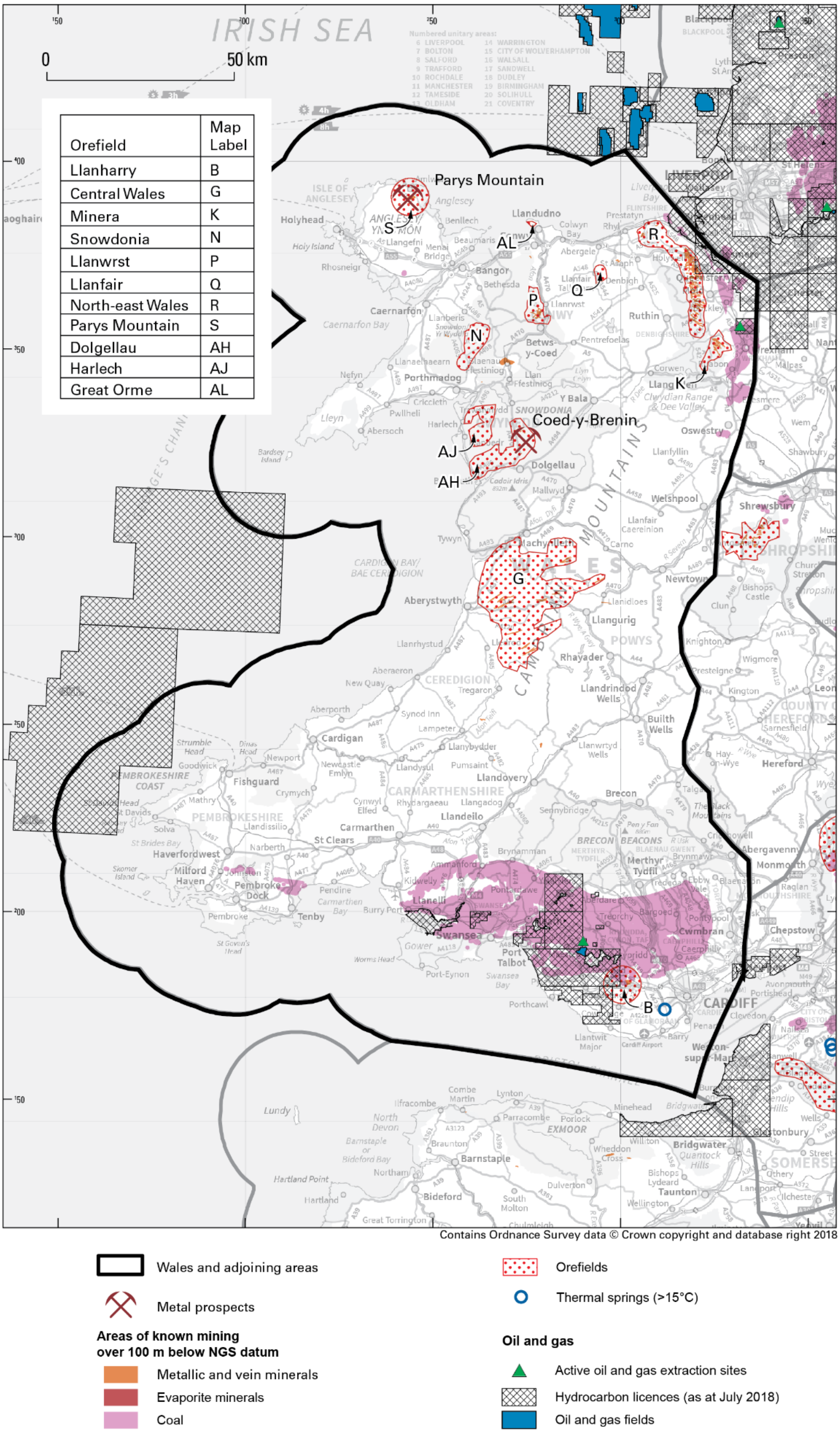

Figure 33 Distribution of mineral resources in Wales. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields and underground 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.

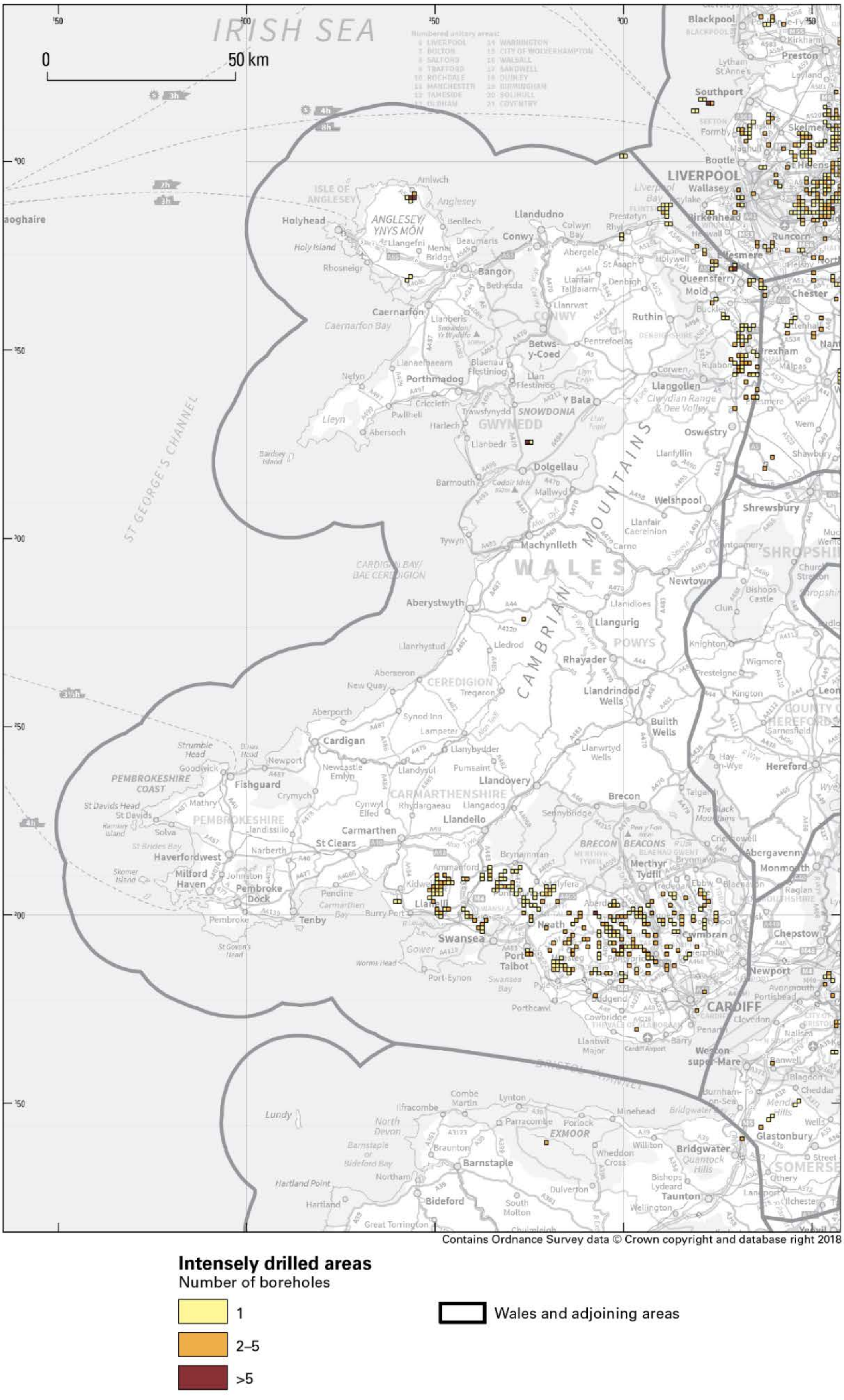

Figure 34 Location of intensely drilled areas in Wales, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

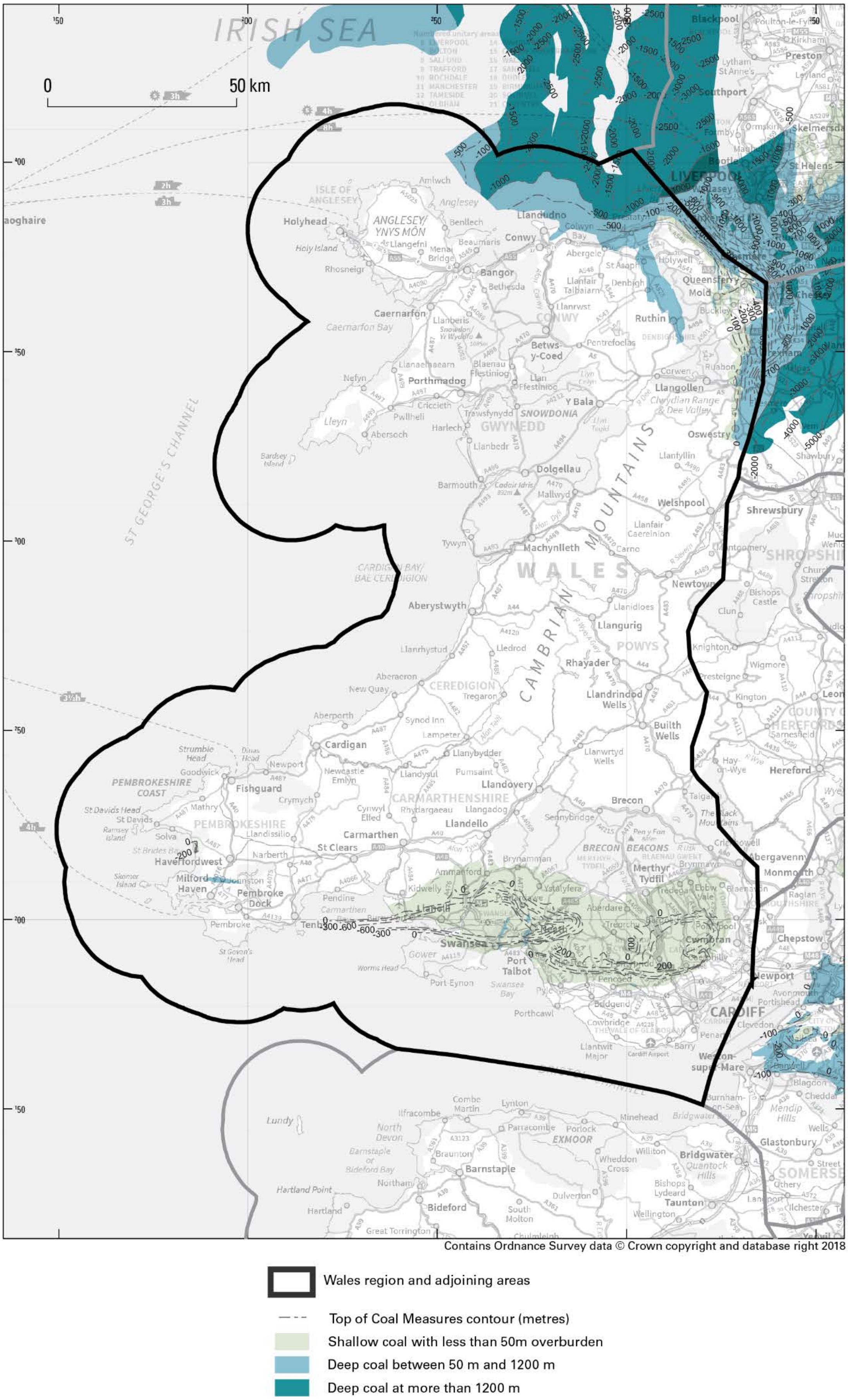

Figure 35 Distribution of coal resources in Wales. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

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 not included within the comprehensive review used to create this dataset. However, it is unlikely these mines will be sufficiently deep to be of concern for NGS. It is also possible that mapped mineral veins do not accurately present the subsurface extent of underground workings. A buffer of 100 m has been applied to all mapped mineral veins to mitigate for this.

8.11.1 Mine depths

Any reported mine depth is often difficult to attribute to a specific datum. This results in a degree of uncertainty about the maximum depth of workings. For example, depths are variously reported as being from surface or adit (or adits) but it is often unclear which is being used and in which area of a mine. Significant additional research, including of historic mine plans and records, would be required to overcome this. 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 over estimate depths where this is not the case.

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

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

1 fathom = 6 feet

1 foot = 0.3048 metres

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

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

8.11.2 Mined extents

The areas of vein-type and related ore deposits (shown on Figure 33) have been depicted where possible by applying a 100 m-wide buffer to the mapped extent of the mineral vein. Where this is not possible, a 100 m buffer has been applied the location of known mines in order to encompass the possible extent of the workings. This approach ensures that any inaccuracies in the mapped vein locations and extent of past workings fall within the boundary of the area identified.

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

8.11.3 Potash, halite, gypsum/anhydrite and polyhalite deposits

The 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 Hydrocarbons (oil and gas)

The hydrocarbon fields displayed on Figure 33 are provided by the hydrocarbon industry to the Oil and Gas Authority. They represent the extent of known hydrocarbon resources usually shown by the oil or gas contact with water within the hydrocarbon trap structure.

The hydrocarbon licence areas displayed on Figure 33 represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place.

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

8.11.5 Coal and related commodities

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

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

8.11.6 Borehole depths

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

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

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Borehole locations

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

Coal resources

The locations of coal resources and areas of deep coal mining have been sourced from the Coal resources map of Britain 1:1,500,000: BRITISH GEOLOGICAL SURVEY, CHAPMAN, G R, and COAL AUTHORITY. 1999. Coal resources map of Britain 1:1,500,000. (Keyworth: British Geological Survey) and the UK Coal resource for new exploitation technologies map:

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The locations of deep evaporite mines and slate mining have been taken from mine plans and BGS records and the BGS BRITPITS database of mines and quarries., Other information on the mineral industry of Wales can be found in the relevant BGS memoir.,

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

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The locations of deep mines for metallic minerals have been sourced from the BGS 1:1,500,000 Metallogenic Resources Map and BGS economic memoirs such as:

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Other information on deep mineral resources has been taken from BGS mineral resources maps for England (http://www.bgs.ac.uk/mineralsuk/planning/resource.html#MRM)

Hydrocarbon resources

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

Information on the locations of prospective areas for shale gas and oil has been sourced from the BGS/DECC regional shale gas studies: http://www.bgs.ac.uk/shalegas/