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National Geological Screening: the Welsh Borderland region

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Foreword

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

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Acronyms and abbreviations

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

Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1 Introduction

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

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

2 Background

2.1 NATIONAL GEOLOGICAL SCREENING GUIDANCE

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

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

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

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

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

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

2.2   DETAILED TECHNICAL INSTRUCTIONS

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

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

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

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

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

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

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

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

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

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

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

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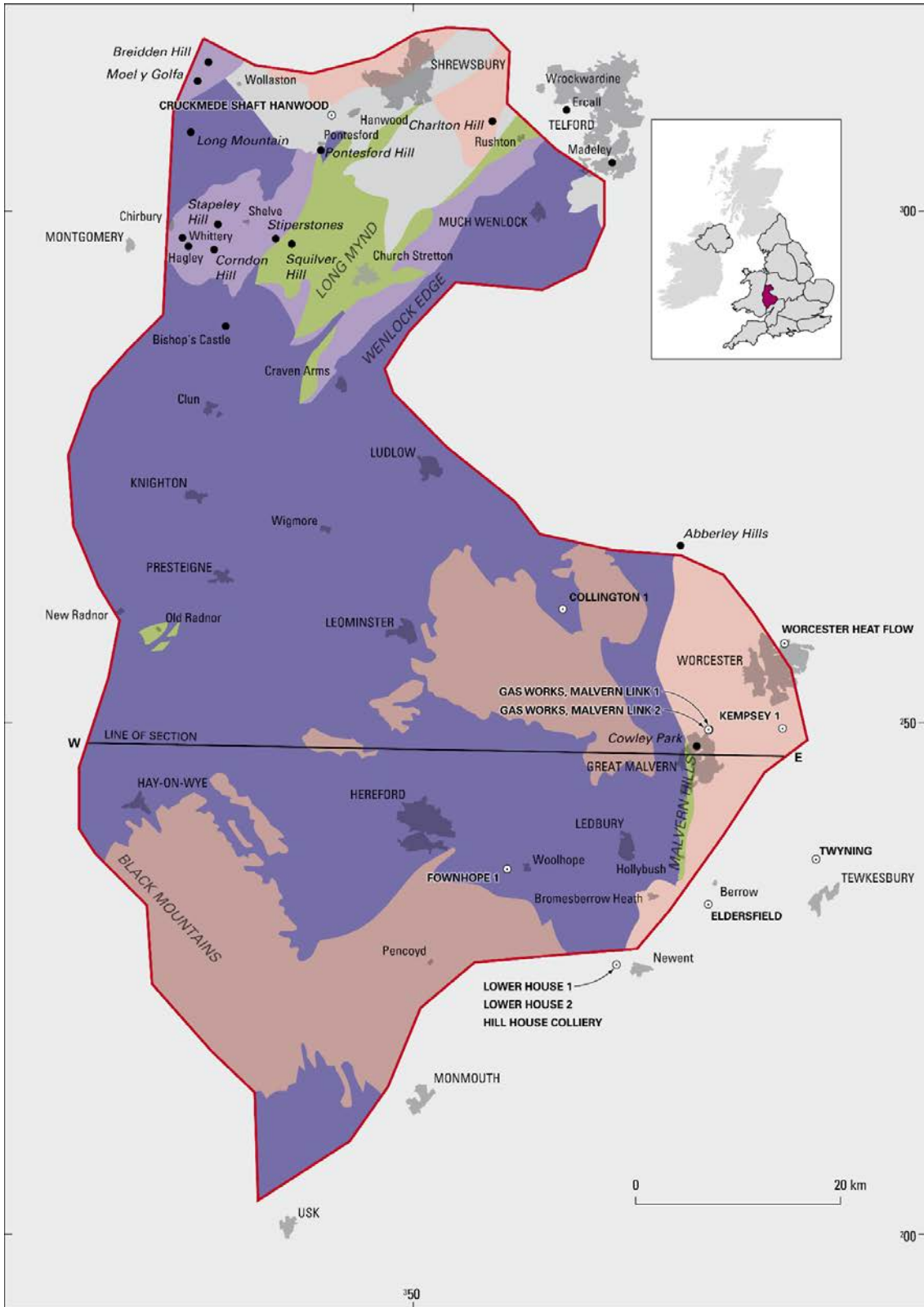
3 The Welsh Borderland region

The Welsh Borderland region comprises south-east Powys, southern Shropshire, northern Gwent, the western half of Herefordshire and Worcestershire, and a small area of northern Gloucestershire (Figure 3). The rocks in the region are predominantly sedimentary in origin, although extrusive lavas and tuffs, igneous intrusions and small areas of metamorphic rocks are present.

The geology of the Welsh Borderland region is mostly known from geological mapping, surface exposures and quarries; the geology at depth is less well known due a paucity of deep exploration boreholes and geophysical seismic reflection profiles. The BGS records show that there are only three records for boreholes drilled below 1000 m depth in the region, compared to 696 in the Eastern England region. However, despite this uncertainty at depth, the near surface geology is well understood from geological mapping and a number of shallow boreholes that allow extrapolation of the near-surface geology to depth. Information on the deeper rocks is mostly clustered in areas where there has been exploration for groundwater and hydrocarbons, and to a lesser extent, for coal in the Shrewsbury and Newent coalfields. In general, our understanding of the geology to the east of the East Malvern Fault (Figure 3) is less certain at depth.

3.1 OVERVIEW OF THE GEOLOGY OF THE REGION

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

The region's diverse landscape reflects the underlying bedrock geology comprising broad, rolling hills, more pronounced ridges of harder rocks, and river valleys. The Welsh Borderland region contains a broad range of rock types, including some of the oldest rocks present in England and Wales. Younger bedrock, comprising the Triassic Mercia Mudstone and Sherwood Sandstone groups, is present to the west of the River Severn, bounded to the west by the north-trending East Malvern Fault; similar rocks crop out around Shrewsbury (Figure 3). An extensive area to the south of Ludlow, including Leominster, Hay, Hereford and Monmouth is underlain by Devonian and Silurian mudstone and sandstone (Old Red Sandstone Group) forming subdued hills and rolling terrain drained by the River Wye and its tributaries, but in the south of the region these rocks form the high plateau of the Black Mountains (890 m above ordnance datum (OD)). In the north of the region, between Telford and Shrewsbury, the southern extension of the Shropshire plain is underlain by Carboniferous rocks, including the Warwickshire Group. South of here older early Palaeozoic rocks and Precambrian 'basement' rocks are found at the surface, forming a subparallel series of prominent north-east-trending hills, ridges and escarpments including (from north-west to south-east): Long Mountain; Shelve Inlier; Stiperstones, The Long Mynd (517 m above OD); Caradoc Hills and Wenlock Edge. Small outcrops (inliers) of these older rocks are present to the south-west, adjacent to the major Church Stretton fault zone. In addition, the early Palaeozoic and Precambrian rocks form the north-trending Malvern Hills (398 m above OD), which are bounded to the east by the East Malvern Fault. To the south, the early Palaeozoic Silurian rocks are again exposed at May Hill, and around Ledbury and Woolhope, surrounded by younger Old Red Sandstone. Farther south, the Silurian rocks are found at outcrop in the Usk area (Figure 3).

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Age (Ma)	Map/section descriptor	Geological sub-units (selected)	Text descriptor
200–300	Permo-Triassic sedimentary rocks	Mercia Mudstone Group Sherwood Sandstone Group Permian sedimentary rocks	Younger sedimentary rocks
300–360	Carboniferous sedimentary rocks	Warwickshire Group South Wales Coal Measures Group Marros Group Millstone Grit Group	Older sedimentary rocks
360–415	Devonian sedimentary rocks	Lower Old Red Sandstone Group	
415–445	Silurian sedimentary rocks	Raglan Mudstone Formation Much Wenlock Limestone	Basement rocks
445–540	Ordovician and Cambrian rocks	Ordovician and Cambrian rocks	
540–680	Precambrian rocks including igneous rocks	Malvern Complex Uriconian Group	

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

Figure 4 Schematic west–east cross-section through the Welsh Borderland region. The line of the section and the key are shown in Figure 3. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.
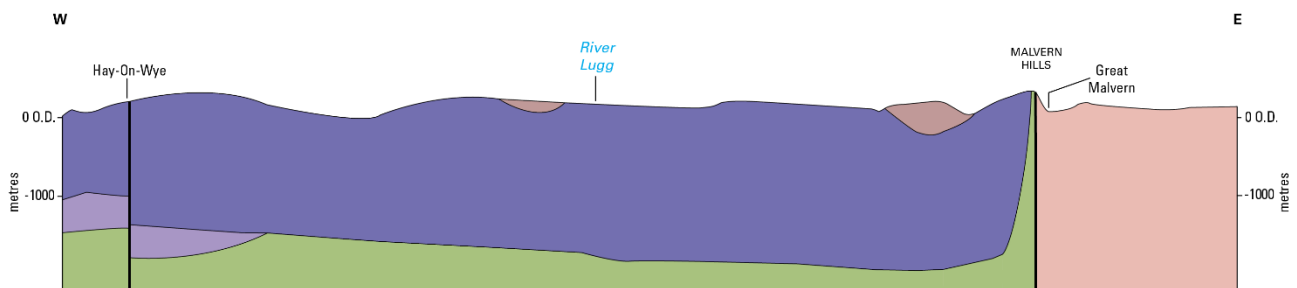
4 Screening topic 1: rock type

4.1 OVERVIEW OF ROCK TYPE APPROACH

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

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

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

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

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

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

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

4.2   POTENTIAL ROCK TYPES OF INTEREST IN THE WELSH BORDERLAND

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

For the Welsh Borderland, the GVS groups the rocks into three age ranges: younger sedimentary rocks (Triassic to Permian), older sedimentary rocks (Carboniferous to Devonian) and basement rocks (Silurian to Precambrian) (Table 3, column 1). 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. The PRTIs in the region comprise solely lower strength sedimentary rock (LSSR) units within the younger and older sedimentary socks; there are no evaporite (EVAP) and higher strength rock (HSR) PRTIs in the region.

The majority of the basement rocks in the region comprising early Palaeozoic sedimentary rocks, lie outside established cleavage belts (Acadian and Variscan) of Wales, the Lake District and south-west England and it is not known whether the mudstone component of these rocks, proved in boreholes and inferred from geophysical and gravity data, preserves a pervasive cleavage, and therefore is sufficiently compacted and metamorphosed (Table 2).Consequently they are not considered to be a PRTI and are not considered further. Potential HSRs of Precambrian age, comprising the harder, denser 'basement' rocks shown in Figure 4, lie mostly below the depth range of interest. A number of small, isolated, disparate outcrops of potential HSRs occur at or near the surface in the region, however these are excluded as PRTIs because their volumes are too small to be adequately represented in cross-sections in the NGS3D model and are not discussed further. These include the Ordovician volcanic rocks and sills and Ordovician intrusive rocks of the Stiperstones and Chirbury areas and the Shelve inlier, together with Neoproterozoic rocks cropping out along the along the north-north-east-trending Church Stretton fault zone and the subparallel Pontesford-Linley fault zone.

The PRTIs are described in Table 3 in stratigraphical order from youngest to oldest (i.e. in downward succession), grouped by the three age ranges: younger sedimentary rocks, older sedimentary rocks and basement rocks. The descriptions include the distribution of the PRTI at surface (outcrop) and where the PRTI is present below the surface (subcrop) within the depth range of interest, along with key evidence for the interpretations. The main geological properties of the PRTIs and how these vary across the region are also summarised.. Data are mostly taken from the BGS Regional Guide to the Welsh Borderland region (Earp and Hains, 1971) 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 3.

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

Maps showing the lateral distribution of PRTIs between 200 and 1000 m below surface, amalgamated into the generic host-rock types (i.e. EVAP, HSR and LSSR) are provided in Figures 5, 6 and 7 respectively. A further map showing the combined lateral extent of all PRTIs is provided in Figure 8. An illustrative GVS (Table 3) summarises the sequence of rocks present in the region and the position within that sequence of PRTIs and principal aquifers.

Table 3 Schematic GVS for the Welsh Borderland region showing units that contain PRTIs and /or principal aquifers. Geological units are generally shown in stratigraphical order and display variable levels of resolution reflecting the resolution within the UK3D model. The units are not to vertical scale and due to

regional variations; some units may be locally absent or may be recognised in different stratigraphical positions from those shown. See Figures 5, 6 and 7 for the regional distribution of PRTIs amalgamated by host rock model (i.e. LSSR, EVAP and HSR respectively).

Geological period		Geological unit identified in NGS3D	Dominant rock type	Potential rock types of interest			Principal aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS	Triassic	Mercia Mudstone Group	Mudstone, with local siltstone and evaporite deposits of anhydrite, gypsum and halite	N/A	Branscombe Mudstone, Sidmouth Mudstone and Tarporley Siltstone formations	N/A	N/A
		Sherwood Sandstone Group	Red sandstone, siltstone and mudstone	N/A	N/A	N/A	Sherwood Sandstone Group
	Permian	Bridgnorth Sandstone Formation (New Red Sandstone Supergroup)	Sandstone	N/A	N/A	N/A	Bridgnorth Sandstone Formation
		Permian rocks (undivided)	Interbedded sandstone and conglomerate	N/A	N/A	N/A	N/A
OLDER SEDIMENTARY ROCKS	Carboniferous	Warwickshire Group	Siltstone and sandstone with subordinate mudstone	N/A	Etruria Formation	N/A	N/A
		South Wales Coal Measures Group	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	N/A	N\A	N/A	N/A
		Marros Group	Mudstone, siltstone, sandstone, coal, ironstone and ferricrete	N/A	N/A	N/A	N/A
		Millstone Grit Group	Coarse-grained feldspathic sandstone, interbedded with siltstone and mudstone	N/A	N/A	N/A	N/A
		Tournaisian–Visean Rocks	Limestone and subordinate sandstone and argillaceous rocks	N/A	N/A	N/A	N/A
	Devonian	Late Devonian	Mudstone. siltstone and sandstone and interbedded sandstone and conglomerate	N/A	N\A	N\A	N/A
		Early Devonian	Mudstone, siltstone and sandstone and interbedded sandstone and conglomerate	N/A	N/A	N/A	N/A
BASEMENT ROCKS	Early Palaeozoic	Pridoli rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Ludlow rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Wenlock rocks (undivided)	Mudstone, siltstone and sandstone, interbedded sandstone and conglomerate	N/A	N/A	N/A	N/A
		Llandovery rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Caradoc rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Llanvirn rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Ordovician volcanic rocks and sills	Tuff	N/A	N/A	N/A	N/A
		Arenig rocks (undivided)	Mudstone, siltstone and sandstone	N/A	N/A	N/A	N/A
		Tremadoc rocks (undivided)	Mudstone, siltstone, and sandstone	N/A	N/A	N/A	N/A
		Cambrian rocks (undivided)	Mudstone, siltstone, and sandstone	N/A	N/A	N/A	N/A
	Early Palaeozoic–Precambrian	Unnamed extrusive rocks (Padarn Tuff)	Tuff	N/A	N/A	N/A	N/A
		Palaeozoic to Proterozoic rocks	Varied	N/A	N/A	N/A	N/A
		Neoproterozoic rocks (undivided))	Varied lithologies	N/A	N/A	N/A	N/A
		Unnamed igneous intrusion	Ultramafic rock	N/A	N/A	N/A	N/A

Figure 5 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Welsh Borderland region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

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

Figure 7 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Welsh Borderland region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.
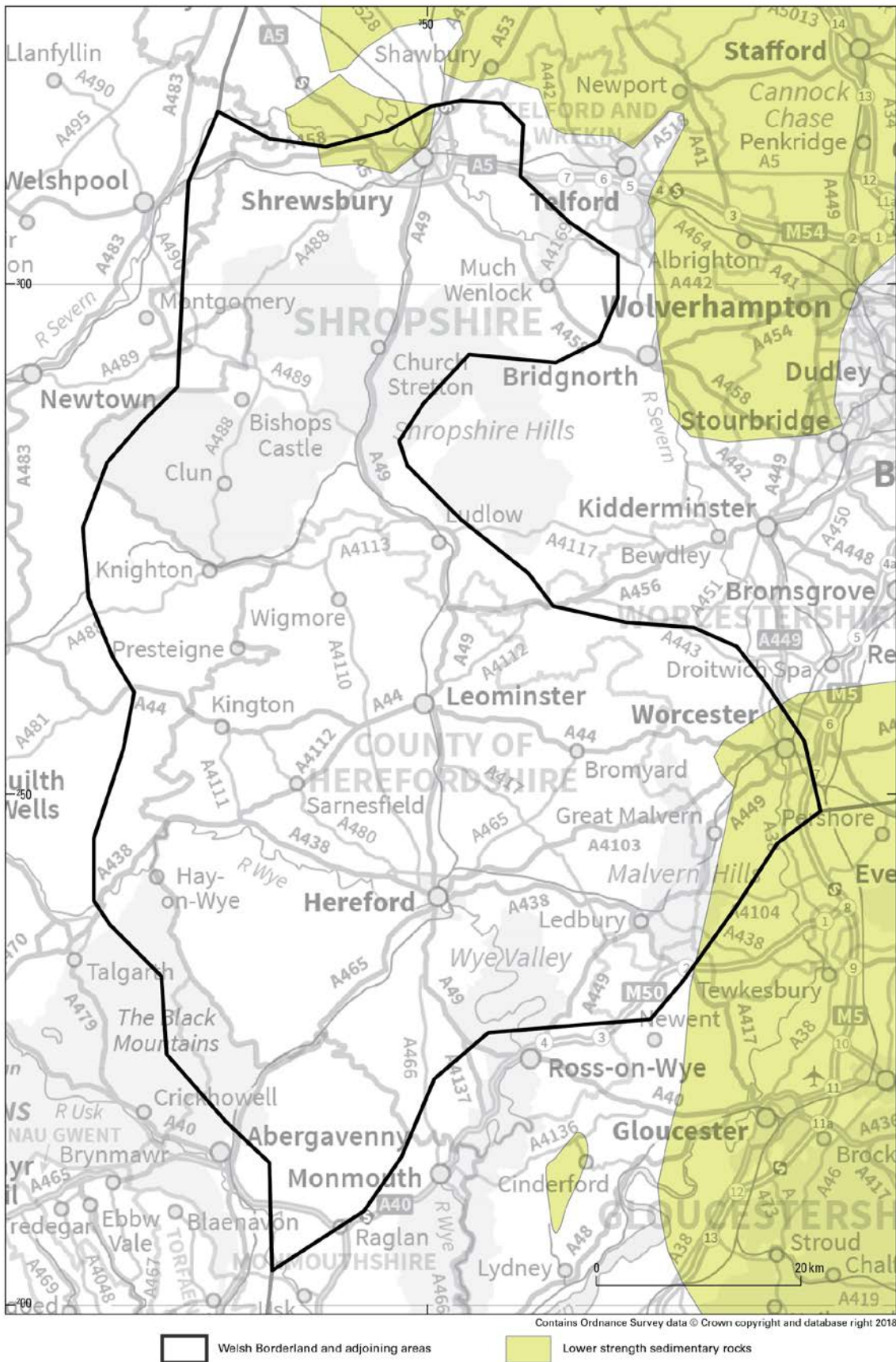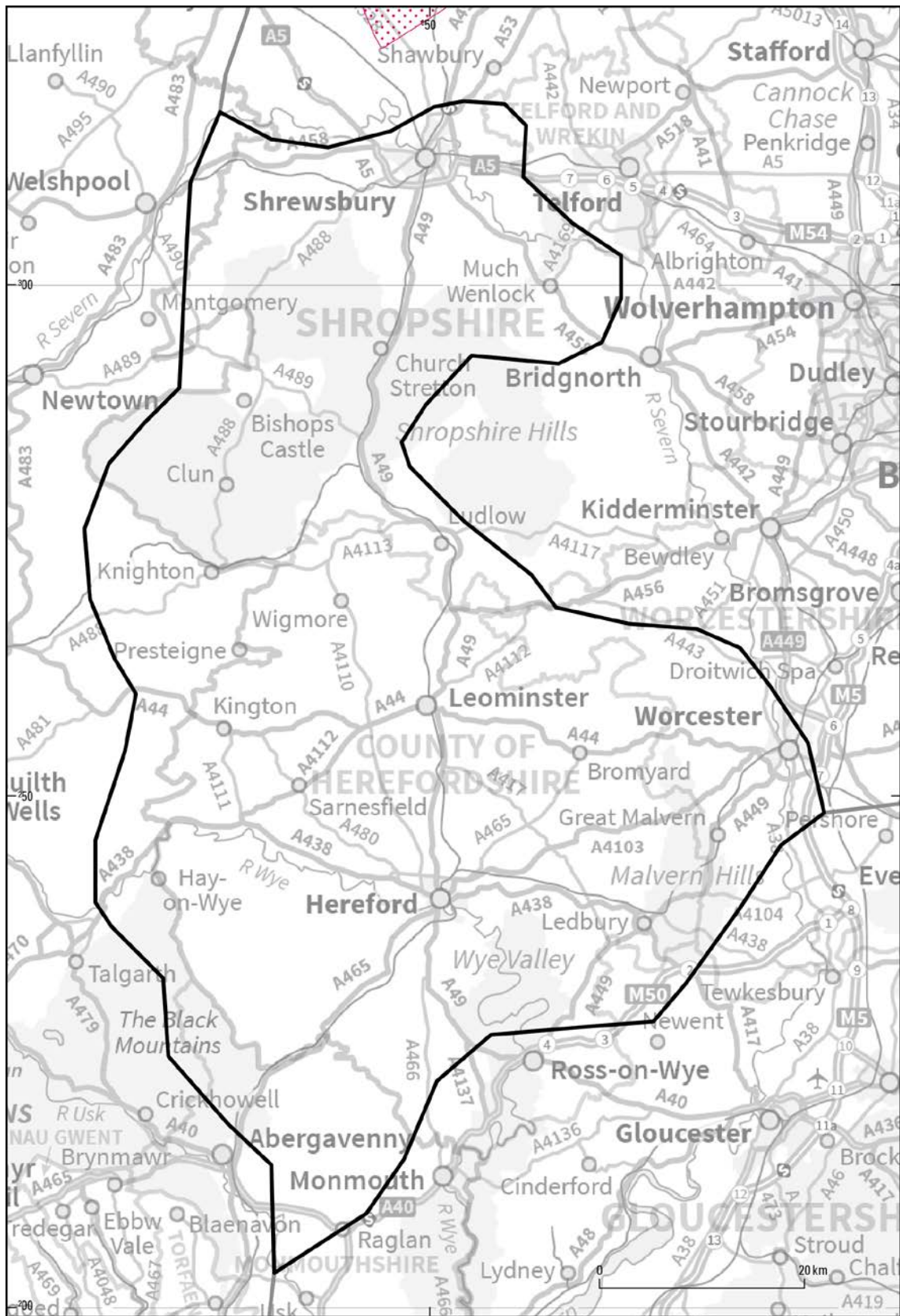
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Figure 8 The generalised combined lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in the Welsh Borderland region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.
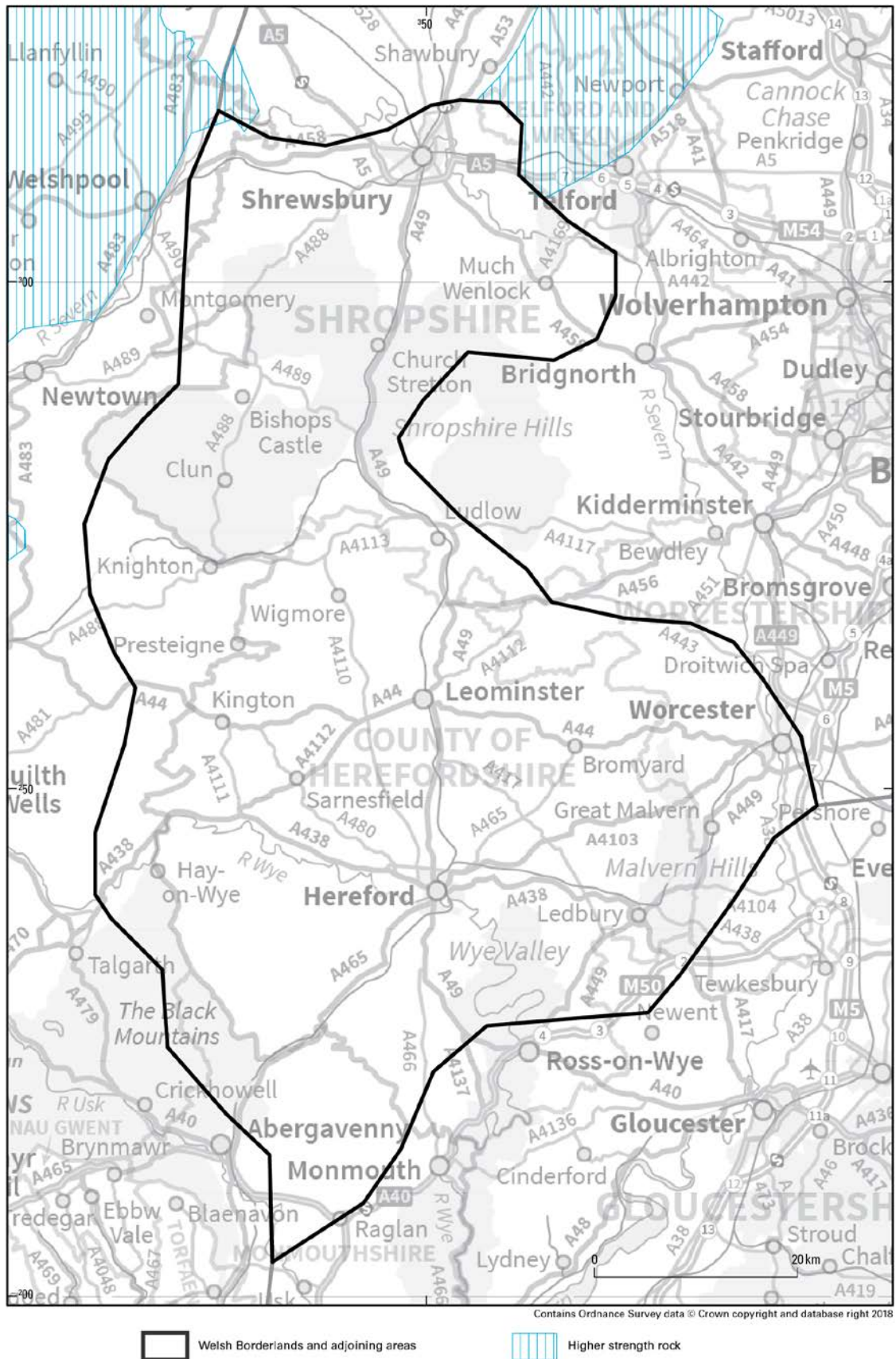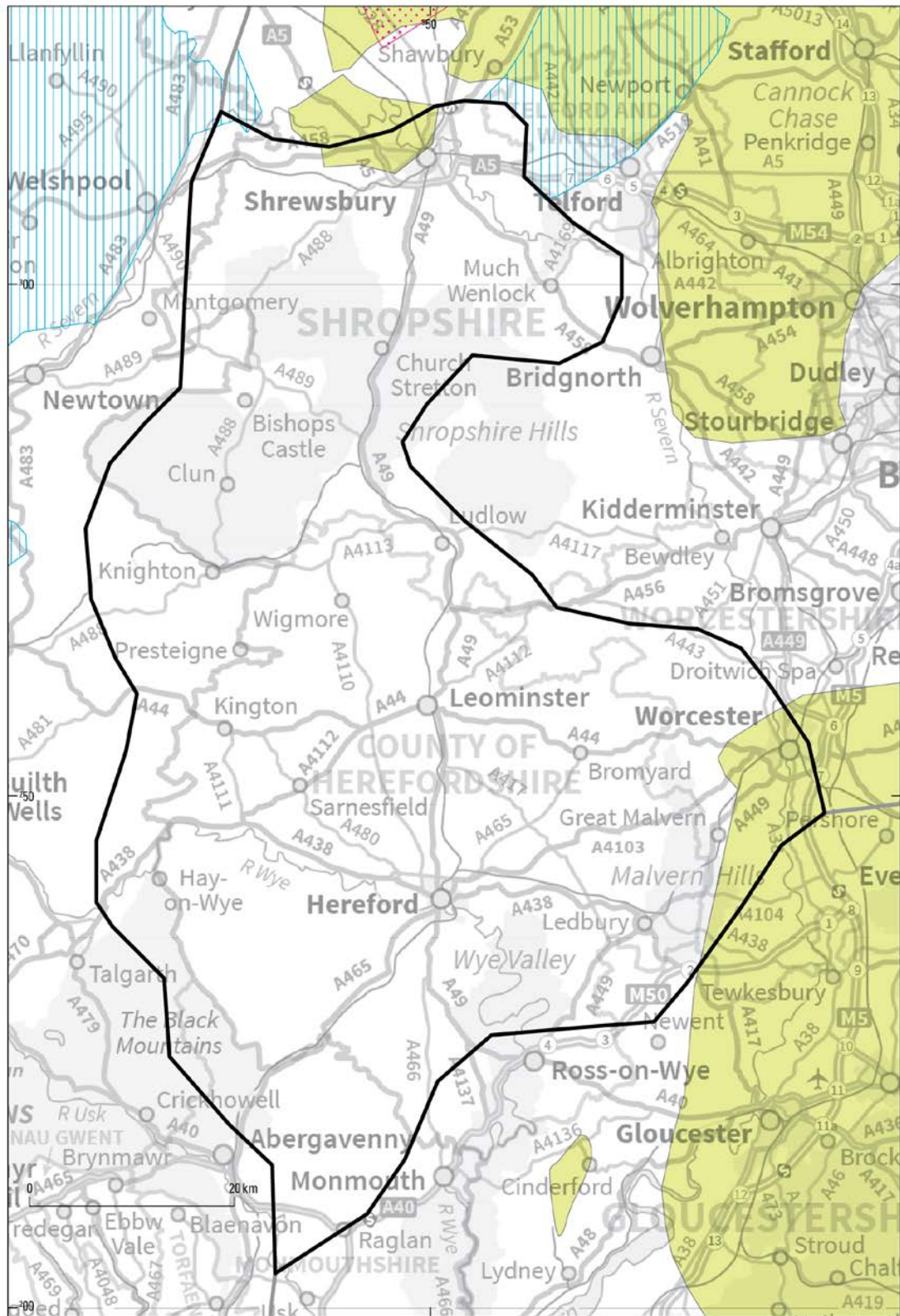
4.2.1 Younger sedimentary rocks

4.2.1.1 MERCIA MUDSTONE GROUP — LSSR

The Mid to Late Triassic Mercia Mudstone Group provides a continuous mudstone-dominated succession with minor sandstones that underlies the Worcester basin area within the depth range of interest. The outcrop (Figure 3) is bounded by the East Malvern Fault, which forms the western margin of the Worcester basin (Earp and Hains, 1971; Worssam et al., 1989; Barclay et al., 1997). The rocks dip at about 1–2º south-eastwards (Figure 4) and are characterised by a topography of low scarps and gentle dip slopes; the Arden Sandstone Member forms a more prominent escarpment. Boreholes indicate that the group ranges in thickness from around 600 and 690 m in the Worcester area, thinning southwards to between 250 and 550 m in the Tewkesbury area (Worssam et al., 1989; Barclay et al., 1997). The formation is underlain by the Sherwood Sandstone Group. The Mercia Mudstone Group is overlain in upward sequence by the Penarth Group and the Lias Group, both of which represent PRTIs. However, the latter two groups lie above the depth of interest and are present only at outcrop on the summit of a small hill at Berrow; consequently, they are not discussed further.

Principal information sources

The surface outcrop of these rocks is well constrained by geological mapping between Worcester and Tewkesbury, although the bedrock is locally obscured by a thin cover of superficial deposits in the west, especially in the area immediately east of the Malvern Hills.

Information on the lithology of the Mercia Mudstone Group (Howard et al., 2008) is sourced from surface exposures, borehole cores and geophysical wireline logs. The group has been penetrated by a few deep cored boreholes in the region and adjacent area to the east (Figures 3 and 9) including the BGS Eldersfield and Twyning boreholes (curated cores are held at BGS), the Malvern Link No. 1 and No. 2 boreholes, Worcester Heat Flow Borehole and the deep exploration Kempsey No. 1 Borehole. These deep boreholes allow the lithology, subdivisions and boundaries of the group to be readily defined at depth, based on information from cores and cuttings, and their distinctive geophysical wireline log signatures (Barclay et al., 1997; Howard et al., 2008). Additional information comes from BGS seismic reflection profiles (BGS 84-01; BGS 84-02 and BGS Stratford) across the Worcester basin, and from gravity and aeromagnetic anomaly data (Barclay et al., 1997).

Rock type description

In this region, five formations are recognised in the Mercia Mudstone Group. Of these, four are recognised as potential LSSR PRTIs. However, only the lowermost three units, the Branscombe Mudstone, Sidmouth Mudstone and Tarporley Siltstone formations are present within the depth range of interest. The Arden Sandstone Formation represents a thin sandstone-dominated unit between the Branscombe Mudstone and Sidmouth Mudstone formations. For completeness the three PRTI subdivisions are described in downward sequence:

The Branscombe Mudstone Formation crops out to the west of the River Severn where it forms gently undulating ground. In the BGS Twyning Borehole it is at least 169.1 m thick, and was proved from 141.5 to 310.51 m depth (Worssam et al., 1989; Barclay et al., 1997), but correlation with the BGS Netherton Borehole, near Evesham, to the east of the region, suggests it is 190 m thick hereabouts. The formation consists mostly of red, blocky mudstone with subsidiary silty mudstone. Gypsum and anhydrite are common as beds, nodules and veins, but these evaporite minerals are absent at depths of between 20 to 30 m from the ground surface due to their dissolution in groundwater. The formation overlies the Arden Sandstone Formation (4.5 m thick in the BGS Twyning Borehole) which consists of grey and green mudstone, interbedded with siltstone and fine- to medium-grained varicoloured sandstone. The proportion of fine to coarse siliciclastics varies laterally throughout the formation (Howard et al., 2008).

The underlying Sidmouth Mudstone Formation ranges in thickness from 371 m in the Kempsey Borehole in the east of the region, to 366 m in the BGS Eldersfield Borehole, near Tewkesbury, where the base lies at 349 m depth (Worssam et al., 1989; Barclay et al., 1997). Seismic reflection profiles show a considerable eastward thickening in the area north of Worcester (Barclay et al., 1997). Approximately 140 m of the Sidmouth Mudstone Formation was proved within the depth range of interest in the Kempsey Borehole, thickening eastward to 520 m in the Netherton Borehole located to the east of the region.

The lithology is similar to the Branscombe Mudstone Formation consisting mainly of red-brown silicate and calcareous mudstone with green patches and thin (up to 4 cm thick) beds of siltstone and, less commonly, fine-grained sandstone, the later locally comprising between 10 to 20 per cent of the rock by volume (Barclay et al., 1997). The thin siltstone and sandstone beds are generally strongly cemented by dolomite and, less commonly, by silica.

At some stratigraphical levels in the area east of Worcester the hard siltstone/sandstone beds are more common, comprising composite units of five or more closely spaced beds known as 'skerries' that form mappable features at the surface. The mudstone is typically blocky and structureless in texture, but other beds are generally well laminated. Gypsum and anhydrite (calcium sulphate) occurs throughout the formation as veins and nodules; dolomite concretions are present at some levels. Halite beds (Droitwich Halite) proved in the upper part of the Sidmouth Mudstone Formation to the east of the River Severn, near Droitwich, are not present in this region

The lowermost sandy part of the group, known formerly as the Holling Member, has been re-assigned to the Tarporley Siltstone Formation (Howard et al., 2008). It comprises mudstone, siltstone and fine-grained sandstone and is 75 m thick in the Kempsey Borehole (where sandstone forms up to 50 per cent of the unit) and about 20 m in the Eldersfield Borehole (where sandstone forms about 20 per cent of the unit).

4.2.2   Older sedimentary rocks

4.2.2.1 WARWICKSHIRE GROUP — LSSR

In this region the Warwickshire Group comprises three formations, in downward sequence: the Salop Formation, Halesowen Formation and Etruria Formation (Powell et al., 2000; 2011) which are present at surface in the Shrewsbury and Newent coalfields (Pocock et al., 1938; Worssam et al., 1989; Waters et al., 2011) and in small areas near the Abberley Hills (Earp and Hains, 1971). The group consists predominantly of red and green mudstone and siltstone with beds of medium to coarse-grained sandstone. In the north-east of the Shrewsbury coalfield the group is overlain unconformably by Permian conglomerates, breccias and sandstones, and to the south-west it rests unconformably on early Palaeozoic and Precambrian rocks (e.g. the Long Mountain and Long Mynd hills).

The Etruria Formation is the only unit of the Warwickshire Group that might represent a PRTI in this region, but it is relatively thin and lies generally above the depth range of interest.

Principal information sources

The group is known from surface outcrops in the Shrewsbury and Newent coalfields and from disused coal mine shafts and exploration boreholes such as the Cruckmede Shaft, Hanwood (Figure 3). In the Shrewsbury coalfield the majority of the disused mine shafts are clustered close to the southern margin of the outcrop where the thin coals in the Halesowen Formation were exploited. Boreholes in the Newent coalfield are clustered around the narrow outcrop west of Newent, a few kilometres to the south-east of the region. Information on the lithology is derived from sparse surface exposures, borehole cores and cuttings.

Rock type description

The Shrewsbury coalfield

The Halesowen Formation consists predominantly of medium to coarse-grained, micaceous sandstone with thin beds of varicoloured silicate mudstone, limestone and coal. The formation is up to 120 m thick (Pocock et al., 1938).

The underlying Etruria Formation is present at surface only at the western margin of the coalfield near Wollaston (Hanwood coalfield), and can be traced along the outcrop for about 6 km to the south-east (Pocock et al., 1938; Earp and Hains, 1971). Mining data indicates that it extends underground eastward towards Great Hanwood area. However, in the Cruckmede Shaft, near Hanwood, the Etruria Formation is absent so that the Halesowen Formation rests unconformably on early Palaeozoic rocks. A similar unconformable relationship is present elsewhere in the Shrewsbury coalfield where sparse borehole/shaft data indicate that the Etruria Formation is cut out below the Halesowen Formation, the latter resting directly (overlapping) onto early Palaeozoic and Precambrian rocks.

The Etruria Formation in this area is about 15 m thick (Powell et al., 2011), and consists of purple and varicoloured mottled, silicate and calcareous mudstone, with a few thin beds of fine-grained limestone; laterally impersistent sandstone beds up to 5 m thick (known as 'espleys') are locally present. The base of the formation lies generally above the depth range of interest, although it may rest at about -230 m depth between Madeley and the Church Stretton fault zone.

Figure 9 Correlation of the Mercia Mudstone Group using gamma ray and sonic logs of boreholes in Worcester and adjacent areas. Locations are shown in the inset map. The current revised nomenclature of the Mercia Mudstone Group is shown. After Barclay et al. (1997). Note the Bromsgrove Sandstone Formation is equivalent to the former Helsby Sandstone Formation (now an obsolete name). British Geological Survey © UKRI 2018.

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The Newent coalfield

Small areas of late Carboniferous rocks are present between the south end of the Malvern Hills and the Silurian inlier of May Hill; the most extensive outcrop is around Newent where thin coal seams were mined in the 19th century along a narrow outcrop; the width of the subcrop is between 1 and 2 km (Earp and Hains, 1971; Worssam et al., 1989; Waters et al., 2011).

The late Carboniferous rocks in this area dip eastwards at about 10º and rest unconformably on, or are faulted against, early Palaeozoic rocks and, in turn, are unconformably overlain by the Triassic Helsby Sandstone Formation.

In this area the Warwickshire Group comprises about 260 m of mudstone, siltstone, sandstone, thin limestones and thin coals termed the Grovesend Formation (Waters et al., 2011), overlying the Stallion Hill Sandstone Formation, 80 m thick (BGS Lower House boreholes nos. 1 and 2). Beds of red mudstone, up to 20 m thick, were proved in the upper part of the Grovesend Formation in the Hill House Borehole (Worssam et al., 1989). In general, the lateral persistence of red and grey mudstone beds is highly variable when traced in boreholes (Worssam et al., 1989). Although the lithology is similar to the red mudstones of the Etruria Formation of the Shrewsbury coalfield, the rocks in the Newent coalfield are more representative of the late Carboniferous rocks lying south of the Wales–Brabant high such as those of the Forest of Dean and Bristol coalfields (Waters et al., 2011). They comprise brown, grey and red blocky mudstones with thin beds of limestone and thin coal seams similar to the Halesowen Formation and, therefore, are not considered a PRTI.

Abberley Hills

The Warwickshire Group also crops out in a small area adjacent to the Abberley Hills (Mitchell et al., 1962; Earp and Hains, 1971). The strata hereabouts belong to the Halesowen Formation (not a PRTI), comprising siltstone and sandstone with thin beds of mudstone, limestone and coal. The beds are steeply folded and rest unconformably on, or are faulted against, the Lower Old Red Sandstone Group. The red mudstone of the Etruria Formation is absent in this area due to overlap of the Halesowen Formation.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in the Welsh Borderland region and shows their surface extent on a map (Figure 11). 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 in this document, are identified.

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

5.2 REGIONAL TECTONIC SETTING

The surface and subsurface structure of the Welsh Borderland region can be described in terms of four major structural events (orogenic cycles) that affected the region and surrounding areas: the Avalonian, Caledonian, Variscan and Alpine orogenies (Pharaoh and Haslam, 2018). Each of these orogenic cycles comprised a

period of crustal extension with basin formation, followed by crustal shortening with basin deformation or (with less shortening) basin inversion. Distinct structures and rock 'units' are associated with each tectonic event, and others characterise the intervening periods.

Most of the region is underlain by the Midlands microcraton, comprising an agglomeration of Avalonian (Neoproterozoic) terranes (Figure 10), as well as parts of the eastern margin of the adjacent early Palaeozoic Welsh basin that is underlain by a separate Avalonian terrane (Wills, 1978; Pharaoh et al., 1987a; Lee et al., 1990; Smith et al., 2005). The crust of the Avalonian terranes is highly heterogeneous and comprises volcanic, volcaniclastic and sedimentary rocks, as well as extrusive and intrusive plutonic complexes that formed and accreted during late Precambrian (700–542 Ma) times (Pharaoh et al., 1987b; Pharaoh and Carney, 2000). The terranes were incorporated into the metamorphic basement of Britain during the Caledonian Orogeny and are divided by a possible sutures (e.g. the Malvern lineament) which exhibit a complex history of Phanerozoic reactivation (e.g. East Malvern Fault).

Figure 10 Principal terranes and basins associated with the Welsh Borderland region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

The Welsh basin represents an area of enhanced subsidence and thick sedimentary deposition that formed in response to extension of the Avalonian basement during early Palaeozoic times. After several phases of subsidence in Cambrian to Silurian times, the basin was inverted during the Acadian phase of the Caledonian Orogeny in Early Devonian (about 395 Ma) times, when construction of a new palaeocontinent, Laurussia, was completed. The associated Acadian deformation was intense, resulting in the development of strong

folding and cleavage (Soper et al., 1987). In contrast, the early Palaeozoic successions deposited on the adjacent Midlands microcraton are generally condensed, typically having a platformal character (Ziegler, 1990) and also less intensely deformed during the Acadian Phase, so cleavage is generally absent (Pharaoh et al., 1987a). Nevertheless, these low-grade metasedimentary, pre-Devonian strata are assigned to the 'basement' in this account.

The boundary between the Midlands microcraton and the Welsh basin transects the region from north-east to south-west, and is marked by a complex zone of south-west to north-east-trending faults known as the Welsh Borderland fault system (Woodcock and Gibbons, 1988). This fault system was reactivated periodically throughout the early Palaeozoic.

Following Laurussia's construction in Early Devonian times, the continent collided with Armorica and other Gondwana-derived terranes, triggering the Bretonian deformation phase (Ziegler, 1990). At this time, the region lay within the southern margin of the Laurussian continent and formed part of the Variscan foreland. During the Late Devonian (Frasnian–Fammenian), north–south crustal extension initiated the development of a set of linked half-graben (Leeder, 1982) which formed part of a basin complex that extended from Ireland to northern England, the East Midlands, Yorkshire and the southern North Sea. Pulsed rifting events continued into late Visean times, resulting in strongly asymmetric depocentres that were infilled largely with sediment in Tournaisian–Visean times.

The Tournaisian–Visean extensional faults were reactivated in compression during the late Carboniferous Variscan Orogeny during consolidation of the supercontinent of Pangaea. The style and magnitude of the associated inversion in the region depends on the orientation of these faults, and that of the basement faults which underlay them (Corfield et al., 1996). These are largely developed in the eastern part of the region, where the most prominent inversion anticlines are associated with northerly trending structures, such as the East Malvern Fault.

Following the Variscan Orogeny, in latest Carboniferous times, the crust of northern central Europe was intruded by alkaline and calc-alkaline magmas (Wilson et al., 2004) as a result of back-arc extension within the Tethys Ocean, transtension and regional thermal collapse (Stampfli and Borel, 2002; Scheck-Wenderoth et al., 2008). This led to extensional collapse of the orogen and localised rifting, for example in the Worcester Graben, north-west-directed extension at this time is inferred from Permian normal faulting in southern Britain (Chadwick and Evans, 1995). Extensional reactivation of Variscan faults under an approximately east–west-orientated extensional regime (Chadwick, 1997) commenced in late Permian times and resulted in the formation of a series of fault-controlled basins in a rift system that extended from the English Channel to the East Irish Sea. The Welsh Borderland region includes the eastern margin of the Cheshire basin, the Stafford basin and the Worcester (Bratch) graben. Locally, up to 3500 m of strata were deposited within these basins by the end of the Triassic, when the UK became part of a major graben system that extended throughout northern central Europe (Scheck-Wenderoth et al., 2008). Crustal extension and the development of syndepositional normal faulting were rapid during the Early Triassic, but less active in Mid to Late Triassic times.

The post-Triassic evolution of the region is poorly constrained due to the paucity of preserved strata. The English Midlands as a whole, including the Welsh Borderland region, occupied a relatively stable, slowly subsiding platform between more rapidly subsiding basins (Pharaoh et al., 2011). During the Cenozoic, the region lay in the foreland of the Alpine–Carpathian Orogen and was affected by a number of pulses of inversion. There has been considerable debate about which of these events was most significant in shaping the Cenozoic exhumation of the region. Brodie and White (1994) and Rowley and White (1997) have argued that regional uplift associated with Palaeocene magmatism was the most significant factor. Other authors have argued that the final, Savian (end-Oligocene/Early Miocene) pulse of the Alpine Orogeny caused significant uplift in the Sole Pit (Glennie and Boegner, 1981), East Irish Sea (Holliday, 1993; Cope, 1997; Green et al., 2000; Holford et al., 2009), Weald and Cleveland basins (Whittaker, 1985), all of which are beyond the limits of the region.

5.3   MAJOR FAULTS AND FOLDS

The major faults selected from analysis of the UK3D model and published maps in the region (Figure 11) exhibit a variety of orientations and evolutionary histories as a consequence of the complex structural history described in this document. In the description that follows, the major faults are described in terms of areas with structures of similar trend. Each area contains a set of faults with a dominant orientation, usually

reflecting the influence of structural control from the underlying basement, and frequently a comparable displacement history, reflecting the behaviour of similarly orientated fault planes to extension or compression in the contemporaneous regional stress field. The terms 'older cover' and 'younger cover' used in this description refer to strata of Devonian to Carboniferous age, and Permian to Jurassic age, respectively. It should be noted that the stated displacement values for faults derived from UK3D and described in this account are for specific locations/levels and are not necessarily characteristic of the whole fault along its length, or indeed its depth. Many faults are long lived, with evidence of repeated reactivation and movement. As such, extensional (normal) displacements tend to be greater at depth, decreasing in the shallower subsurface. Areas of folding pertinent to this study have been identified (Figure 11) and described.
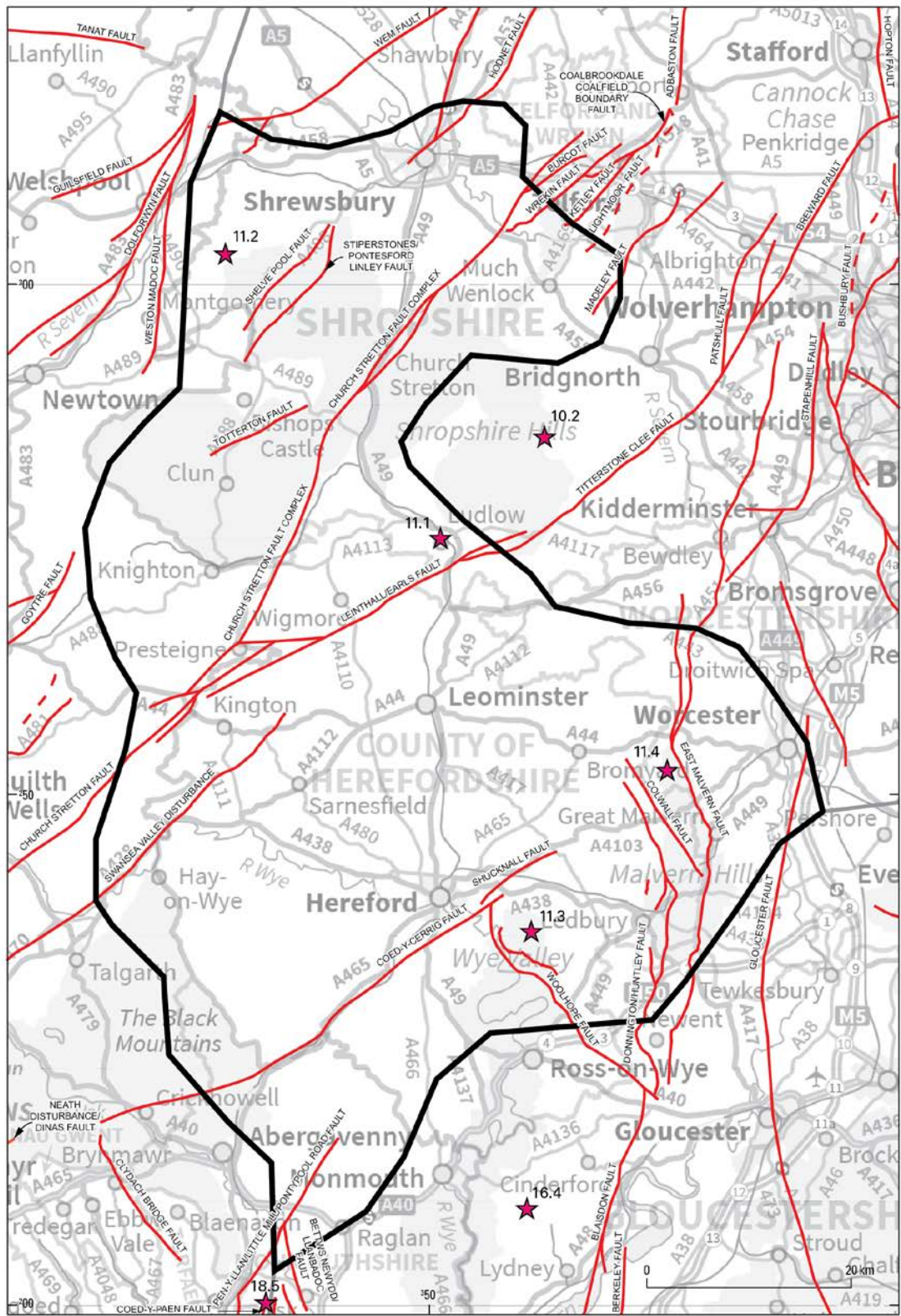
5.3.1 North-east-trending structures

The north-east-trending faults occur across most of the region, except in the far south and east, and inherit their trend from the underlying Caledonian basement. Many of them have a complex reactivation history and they collectively comprise the Welsh Borderland fault system (Woodcock and Gibbons, 1988), which formed the boundary between the Midlands Microcraton and the Welsh basin throughout early Palaeozoic times. The Precambrian rocks are restricted to the fault system and are generally strongly folded, preserving steeply inclined strata. Precambrian basement (Uriconian Volcanic Group and Longmyndian Supergroup) is incorporated in inferred transpressional duplex structures between the Stiperstones/Pontesford Linley and Hodnet faults, and similarly within the Church Stretton fault complex (the Stanner Hanter complex, between Kington and Presteigne). The north-east-trending Church Stretton fault complex has a mapped length of at least 121 km, with both normal and reverse throws of up to 935 m in early Palaeozoic strata at crop (throw derived from the UK3D model).

The Hodnet Fault, a continuation of the regional Pontesford lineament (Woodcock, 1984), has a throw exceeding 200 m in Permo-Triassic strata (Chadwick et al., 1999). The Shelve Pool and Stiperstones/Pontesford Linley faults, also constituents of the Pontesford lineament, have lengths of at least 13 km and 16 km, and throws greater than 300 m and 250 m respectively (as shown in UK3D). The Lightmoor Fault, in the north-east of the region, lies about 8 km to the east of the Church Stretton fault complex and has a normal throw of 270 m in early Palaeozoic strata (as shown in UK3D). The Madeley Fault lies subparallel to this with an estimated throw to the east greater than 300 m (as shown in UK3D), but there are no published accounts of its displacement. The Titterstone Clee/Leinthall–Earls Fault splays off the Church Stretton fault complex in the vicinity of Presteigne and turns north-east to become parallel to it, controlling the eastern margin of the Permo-Triassic Stafford basin; it is at least 85 km long and has a reverse throw of about 250 m in early Palaeozoic strata (throw derived from the UK3D model).

The Palaeozoic strata of the domain are generally only weakly deformed with regional-scale, open folding giving rise to gentle dips, except adjacent to some major faults where more intense folding is present. The folds trend north-east and include the Ludlow Anticline (Figure 11, location 11.1), which is located between the Church Stretton and Titterstone Clee/Leinthall-Earls faults and exposes strata of Silurian age in its hinge zone. Adjacent to this are the Brown Clee and Titterstone Clee synclines, both of which preserve Carboniferous Coal Measures strata in periclinal hinge zones (Greig et al., 1968).

In the north-west of the region, between the Stiperstones/Pontesford Linley Fault and the Dolforwyn Fault in the adjoining Wales region, are a series of north-east-trending folds (Figure 11, location 11.2). The regional scale Shelve Anticline exposes Ordovician strata in its hinge zone, which passes south-west into a complex zone of folding and faulting which forms part of the Welsh Borderland fault system known as the Clun valley disturbance (Cave and Hains, 2001). To the north-west of the adjacent periclinal closure is the Long Mountain Syncline, which preserves strata of latest Silurian age in its hinge. Based on the strength of their deformation, the Precambrian strata in the Long Mynd inlier to the south-east of the Stiperstones/Pontesford Linley Fault are interpreted to reside in the overturned limb of the south-east-verging regional scale Long Mynd syncline (Whittard 1952).

In the south-west of the region is the Swansea valley disturbance and the Coed-y-Cerrig faults, which trend parallel to the Church Stretton fault complex. The Swansea valley disturbance comprises a belt of north-east-oriented faults forming a zone up to around 2 km wide with locally developed folds (Weaver 1975). A vertical downthrow toward the north-west by 30 to 550 m, and a sinistral transcurrent displacement of 280 m, are both reported (Owen and Weaver 1983). The Coed-y-Cerrig Fault, represents an extension of the Neath disturbance that transects the Wales region. Together, these comprise a complex zone of north-east-trending faults with vertical and lateral displacements associated with impersistent north-east-trending

Figure 11 Major faults and areas of folding in the Welsh Borderland region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

folds (Owen 1953). Displacement on the Coed-y-Cerrig Fault is interpreted to be between 15 and 200 m vertical throw down to the north with lateral displacement of up to 1200 m based on interpretation of surface geological mapping (Owen and Weaver, 1983). The normal Shucknall Fault is also considered an along-strike extension of the Neath disturbance, and preserves a broadly synformal structure on its western flank (Brandon 1989, Barclay and Smith 2002). The Totterton Fault trends north-east to south-west, has a mapped length greater than 10 km, and throws Silurian mudstones by at least 400 m to the north (as shown in UK3D).

The Wem Fault just impinges into the far north of the region from the adjoining Central England region. The fault has a throw exceeding 2500 m to the north-west at the base Permo-Triassic level (Chadwick, 1997).

5.3.2   North–south and north-west-trending structures

Faults in the eastern part of the region have a predominantly north–south orientation. This trend, subparallel to the Malvern lineament, a strong north–south-trending geophysical anomaly, is thought to be controlled by Caledonian and Variscan reactivation of a fundamental Avalonian structure in the Neoproterozoic basement (Pharaoh and Carney, 2000). Available seismic reflection data resolve the main controlling faults as high angle, down-to-west, easterly dipping thrusts or reverse faults, formed during Variscan inversion (Chadwick et al., 1983; Chadwick and Smith, 1988; Barclay et al., 1997). Permian faults have up to 2500 m of normal displacement and are usually synthetic to an underlying thrust, though significant antithetic normal faulting can also be present. The East Malvern, Gloucester and Donnington–Huntley faults are examples of Permian faults in the Welsh Borderland region and define the western margin of the Permo-Triassic Bratch Graben (sub-basin of the Worcester graben); further south, the graben's margin is defined by the Berkeley Fault. Together, these structures form the Malvern lineament (Kellaway and Hancock, 1983) and correlate with a strong geophysical signal termed the Malvern lineament. The normal, down-to-east East Malvern Fault, which forms the eastern boundary fault of the Malvern Horst and the western limit of the younger cover in the Bratch graben, is the clearest example of the extensional reactivation of the Malvern lineament during early Mesozoic times. It is mapped over a length of around 75 km in the adjacent Central England region, with over 600 m of displacement in UK3D, and continues to the south into the Bristol and Gloucester region. The Donnington–Huntley Fault and Colwall Fault run parallel to the East Malvern Fault. The Donnington–Huntley Fault has a mapped length of greater than 15 km and a normal throw of at least 700 m to the east, and extends southwards into the Bristol and Gloucester region, whilst the Colwall Fault has a mapped length greater than 13 km and a reverse throw of at least 1000 m to the west (as shown in UK3D). Northward, and *en échelon* to the Donnington–Huntley Fault, are two unnamed faults with lengths greater than 11 km and 13 km and reverse throw of at least 500 m to the west and normal throw of 700 m to the east, respectively (as shown in UK3D).

The Woolhope Fault trends north-west from the south-east margin of the region to transect the Neath disturbance, which was reactivated during the Variscan Orogeny as a south-west directed thrust. The Woolhope and May Hill anticlines developed in the hanging wall of this structure, and both comprise north-west-trending periclines exposing Silurian rocks in their hinges. Further south, the main north–south-trending periclinal Forest of Dean syncline lies in its footwall (Figure 11, location 11.3; Barclay and Smith, 2002).

Concealed beneath the Mesozoic cover near the eastern margin of the region is the Gloucester Fault, a normal, fault, downthrown to the west, with a mapped length of 67 km and a displacement of 590 m in the Triassic strata (as measured in UK3D).

Folds in this area are largely north-north-west-trending and developed in early Palaeozoic strata to the west of the Malvern lineament, effectively forming a complex footwall anticline to the Bratch Graben (Figure 11, location 11.4). Local structures include the Collington, Brockhampton, Horsham, Little Witley, Trimpley and Hazel Farm anticlines, and the Malvern and Mathon synclines (Mitchell et al., 1961, Barclay et al., 1997).

In the south of the Welsh Borderland region, the Pontypool Road Fault, Pen-y-llan Fault and Little Mill Fault form a plexus of structures that define the northern boundary of the periclinal Usk anticline (Location 18.5) 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 estimates of sinistral transcurrent movement range between 200 and 1000 m (e.g. Barclay 1989). The intersecting Betws Newydd Fault (Barclay, 1989) is an ill-defined extension of the Llanbadoc Fault, which juxtaposes older and younger Silurian strata along the eastern flank

of the Usk anticline and downthrows to the east by up to an estimated 150 m (Barclay, 1989). The Coed-y-paen Fault lies on the western flank of this anticline and similarly juxtaposes older and younger Silurian strata, with a preserved downthrow of 80 m on its western side (Squirrell and Downing, 1969). Folding in this part of the region is dominated by the South Wales syncline and adjacent Usk anticline. These comprise the main Variscan fold structures lying to the north of the Variscan fault and fold belt (Hancock et al., 1983). The Usk anticline comprises a north-trending pericline exposing Silurian strata in its hinge zone and is thought to have initiated as a Caledonian structure (Barclay, 1989). For more details on the Usk and South Wales folds see the Wales region.

5.4 UNCERTAINTY

Faults and folds in the Welsh Borderland region are only locally constrained by seismic investigation, located in the south and east, south of a line between Ludlow, Hereford and Abergavenny. They 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 where distinctive units of strata are offset relative to one another, horizontally (slip) and/or vertically (throw), and in a normal or reverse sense. The degree of confidence with which they are mapped is largely dependent upon the quality and density of outcrop information. 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. Consequently, the portrayal of such faults as a single line on the geological map is a generalisation.

Across much of the region 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 the Welsh Borderland region, the regional groundwater flow systems, and any units or structures that may lead to the effective separation of deep and shallow groundwater systems including evidence based on groundwater chemistry, salinity and age. It describes the hydrogeology of PRTIs (or their parent units), principal aquifers and other features, such as rock structure or anthropogenic features (including boreholes and mines), that may influence groundwater movement, and interactions between deep and shallow groundwater systems. It also includes a note on the presence or absence of thermal springs (where groundwater is >15º C) that may indicate links between deep and shallow groundwater systems.

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

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

6.2 GROUNDWATER SYSTEMS IN THE WELSH BORDERLAND

Across the region there is very limited information related to groundwater, either in terms of groundwater movement or chemical composition, in the depth range of interest. Almost all the information is related to the relatively shallow groundwater systems which are currently exploited only in a very limited manner for groundwater resources. Groundwater movement and chemical composition can vary significantly over short lateral and vertical distances even in the depth range of interest. Consequently, the level of uncertainty related to groundwater systems in the depth range of interest is high. It will be important to develop a detailed understanding of groundwater movement and chemistry and their implications for a safety case during any future siting process or site characterisation.

6.3 OVERVIEW OF REGIONAL-SCALE GROUNDWATER FLOW AND HYDROSTRATIGRAPHY

The landscape of the Welsh Borderland region varies from broad rolling hills to steep ridges and valleys and this topography has allowed for the exposure of a large sequence of Palaeozoic and Mesozoic rocks (Earp and Haines, 1971). The regional groundwater systems of the Welsh Borderland region are controlled by; i) the broad distribution of geological units (Table 3) and the regional geological structure, ii) the hydrogeological characteristics of those units and, iii) topography and the distribution of recharge. The

overall hydrostratigraphy of the region is conceptualised as consisting of two groundwater systems based on broad geological divisions, as follows:

- older sedimentary rocks of Devonian to Carboniferous age and younger sedimentary cover rocks of Permian to Jurassic age
- basement rocks and igneous intrusions of Proterozoic to Ordovician age

The groundwater system that is comprised of basement rocks is the most extensive in the region, but is the one for which there is least hydrogeological information, even from near outcrop. The other groundwater system, consisting of Devonian to Jurassic rocks, is found within two small subareas of the Welsh Borderland region. Both these subareas represent the extension of much more extensive basins to the north and east of the region: the southern part of the Cheshire basin, which occurs in the north of the Welsh Borderland near Shrewsbury (Allen et al., 1997; Smedley et al., 2005), and the western part of the Worcestershire basin (Allen et al., 1997; Tyler-Whittle et al., 2002) in the east of the region. Consequently, the hydrogeology of the younger and older sedimentary sequence and associated aquifers are more comprehensively described within the adjacent Central England region report.

Although groundwater development is relatively limited compared with other regions, the Sherwood Sandstone Group is a principal aquifer and provides some water supply in the region. Other locally important aquifers occur in the region such as Carboniferous Warwickshire Group and units within Silurian and Devonian aged rocks, which are used for public and private drinking-water supply, and industrial and agricultural purposes (e.g. Jones et al., 2000; Moreau et al., 2004; Environment Agency Wales, 2008).

Rocks from both of the groundwater systems are found in the depth range of interest across the region. Potential pathways for groundwater movement between units are described after the two groundwater systems are discussed in the following sections.

6.3.1 Hydrogeology of the cover sequence

The Permo-Triassic strata are the stratigraphically youngest and highest part of the sedimentary bedrock sequence in the region. The Sherwood Sandstone Group and underlying Helsby Sandstone Formation, form the only principal aquifer in the Welsh Borderland. Geographically there are two separate areas of the Permo-Triassic aquifer in the Welsh Borderland, the largest occurring in the south-east, in Worcestershire, (Allen et al., 1997; Tyler-Whittle et al., 2002) and the other in the north of the region near Shrewsbury.

The Mercia Mudstone Group rocks are bounded by the East Malvern Fault, in the eastern area of the region. The group ranges in thickness from around 600 to 690 m in the Worcester area, thinning southwards to between 550 and 250 m in the Tewkesbury area (Worssam et al., 1989; Barclay et al., 1997) and is underlain by the Sherwood Sandstone Group principal aquifer. Hydrogeological information on the Mercia Mudstone Group in the Worcester basin is included in the Bristol and Gloucester district region companion report.

The most extensive area of the Permo-Triassic principal aquifer in the Welsh Borderland region is associated with the western part of the Worcestershire basin, which forms the eastern part of the region. In this area the Permo-Triassic strata are downfaulted to the east, by the East Malvern Fault, bringing them in contact with Silurian strata. The hydrogeological effect of this fault to act as either a zone of relatively high transmissivity, or a boundary to groundwater movement, is unknown. Typically, the Sherwood Sandstone Group acts as a single hydrogeological unit, unless present mudstones layers can cause hydraulic separation (Allen et al., 1997). Faulting is common; however, there has been no systematic survey of faults or their effect on the hydrogeology of the sandstones (Allen et al., 1998) in the region. Baseline geochemical data studies in the Stour groundwater catchment (Tyler-Whittle et al., 2002) located within the Worcester basin, to the east of the region and within the adjacent Central England region, may provide the closest proxy for groundwater chemistry within the Permo-Triassic aquifer. Groundwater samples were obtained from the Kempsey Borehole (SO86094933) located on the eastern margin of the region; this borehole proved 2305 m of Permian and Triassic strata underlain by 760 m of Precambrian volcaniclastic rocks. Groundwater samples from the Permian formation water have lower chloride concentrations when compared to groundwater analysis from other Permo-Triassic basins (e.g. Wessex Basin); this has been interpreted as indicating recharge to the aquifer during the Quaternary rather than Tertiary Period (Darling, et al., 1997).

The Permo-Triassic principal aquifer also occurs near Shrewsbury in the north of the Welsh Borderland region, representing the most southern part of the Cheshire basin (Smedley et al., 2005) most of which occurs to the north within the adjacent Central England region. Here the aquifer is at a shallow depth and

above the depth range of interest. The aquifer properties of the Permo-Triassic Shropshire aquifer have been dealt with in the Central England region companion report. The groundwater chemistry, within the wider Permo-Triassic sandstone aquifer of Shropshire has been described by Smedley et al. (2005). Calcite dissolution is an important process influencing groundwater chemistry, reflected by the dominant Ca-HCO$_3$ groundwater facies (Smedley et al., 2005). Vertical leakage from the overlying superficial aquifers can occur in areas such as the Severn trench to the west of Shrewsbury (Smedley et al., 2005).

In the Welsh Borderland region, the Etruria Formation of the Carboniferous Warwickshire Group has been describe by Jones et al. (2000) as poorly productive but there is no other information on the hydrogeological characteristics of this unit in the references reviewed.

The Old Red Sandstone Supergroup is not a principle aquifer and is therefore not shown in Table 3, however it is a locally important aquifer (e.g. Richardson, 1935; Jones et al., 2000; Moreau et al., 2004). These sedimentary rocks cross the boundary between the Silurian and the Devonian (Jones et al., 2000) and mark a transition from the underlying Silurian sedimentary rocks (Earp et al., 1971). Hydrogeological summaries of the Old Red Sandstone Supergroup are included in geological memoirs (Richardson, 1935; Greig et al., 1968; Mitchell et al., 1962, Barclay, 1989; Barclay et al., 1997), however, they are most recently described in Jones et al. (2000). The supergroup is a complex, multilayered aquifer of contrasting properties from low permeability marls to higher permeability calcrete deposits, with groundwater flow and storage dominated by fractures and joints (Jones et al., 2000). Pumping tests indicate that it is heterogeneous, both laterally and vertically (Jones et al., 2000). The majority of hydrogeological observations are associated with the Late Devonian Upper Old Red Sandstone, as this is the main water-bearing unit within the Devonian sequence. However subordinate sandstones, including the Downton Castle and Holdgate sandstones in the Silurian, older part of the Lower Old Red Sandstone can transmit water (Jones et al., 2000).

There is very limited hydrogeological information for the Silurian Raglan Mudstone in the region. The main studies have been undertaken in the adjacent Wales region (see Wales region companion report and references within including: Neal et al., 1997; Robins and Davies, 2016; Shand et al., 2005).

6.3.2 Hydrogeology of the basement rocks and igneous intrusions

The Malvern Complex and Uriconian Group of the Precambrian Basement are generally steeply inclined and up to 1200 m thick (Jones et al., 2000). The late Precambrian rocks (Malvern Complex) of the Malvern Hills include both intrusive and extrusive igneous rocks, all of which have been affected by intense deformation (Jones et al., 2000)). There is very limited information on the hydrogeology of the Ordovician igneous rocks and Precambrian (Neoproterozoic) basement rocks. However, Jones et al., (2000) suggest that the principal controls on the properties of pre-Devonian aquifers are the degree of induration and cementation, as well as the extent and depth of fracturing, with flow and storage almost entirely controlled by fractures. There is no information on the hydrogeological of units in this groundwater system in the depth range of interest in the references reviewed.

6.4 EVIDENCE FOR CONNECTIONS BETWEEN GROUNDWATER SYSTEMS

6.4.1 Geological pathways

There is no evidence in the reviewed literature for relatively rapid subvertical flows from the depth range of interest to the current land surface and there are no known thermal springs within the Welsh Borderland region. Thermal springs are defined for the purpose of this assessment as springs with temperatures >15 °C.

Over a range of scales, faults within the region may act to compartmentalise groundwater by reducing flow across the structures, while in other cases they may act to enable enhanced flow of groundwater and may be associated with localising flows from depth to surface springs. In addition, faults may disrupt or enhance local groundwater flow by juxtaposing more or less permeable units either side of fault strands and may localise flow to springs. In the region, the two groundwater systems are relatively geographically distinct and are primarily separated by major structural lineaments and features (see Section 5). There is no information about the effects that such large-scale structures have on the hydrogeology of the region. In addition, there is a paucity of deep boreholes (>200 m deep) and also information about aquifer characteristics at depth in the region. Consequently it is not possible to assess the nature of any hydrogeological connections between the two groundwater systems. However, some observations can be made regarding hydrogeological characteristics in the depth range of interest based on groundwater temperature data for the region. During the 1970s research on deep geothermal energy resources across the UK resulted in the measurement of deep

groundwater temperature across England and Wales (Burley and Gale, 1981). Groundwater temperatures were measured in several boreholes including Malvern Gas Works (SO788492; 245 m deep) and Kempsey (SO86094933; 3003 m deep) resulting in measured temperature gradients of 17.6 and 17.4 $^{\circ}$C /km (Burley and Gale, 1981). Geothermal gradients can be variable, the average geothermal gradient in the UK is 28 $^{\circ}$C per kilometre within the upper 1 km of crust, based on measured and estimated temperatures at intervals of 100, 200, 500 and 1000 m (Busby et al., 2011).

6.4.2   Anthropogenic features

There are very few intensively drilled areas in this region (see Section 8.10). There is one area of deep boreholes (greater than 200 m below NGS datum) with a density of two boreholes per square kilometre north of Great Malvern which have been drilled for site investigation for infrastructure projects.

Subsurface mining can create anthropogenic pathways, within local bedrock aquifers, facilitating the circulation of groundwater/mine water within mine systems. Evidence of historical coal mining is restricted to a small area in the Shrewsbury coalfield, in the Halesowen Formation (formerly Coed-yr-Allt beds) at a maximum depth of 150 m (Earp and Hains, 1971), and a small area in the Newent coalfield. The effect of the abandoned mine workings on the local hydrogeology in these areas is not known. Metal mines associated with Ordovician strata (vein minerals) in the Shropshire orefield, occur in small areas to the south-west of Shrewsbury worked to more than 500 m below the surface. First exploited in Roman times, all operations had ceased by 1945 (Earp and Hains, 1971). The effect of the abandoned metal mine workings on the local hydrogeology is not known.

7 Screening topic 4: natural processes

7.1 OVERVIEW OF APPROACH

Over the next one million years and beyond, a range of naturally occurring geological processes will continue to affect the landscape and subsurface of the UK. These processes have been active on and off throughout geological history and are likely to occur in the future. The range of processes and their impacts have been extensively reviewed by Shaw et al. (2012). However, only some of these natural processes are considered likely to affect the subsurface at the depth range of interest. These include glaciation, permafrost, seismicity and the effect of sea-level change on groundwater salinity (Shaw et al., 2012). Other naturally occurring geological processes that will occur over the next million years, such as surface erosion, surface weathering, tectonic uplift and subsidence, are not considered to be significant within the depth range of interest (Shaw et al., 2012).

This section provides an overview of the natural processes that may affect rocks to depths of between 200 and 1000 m in the Welsh Borderland region, specifically within a broader national context (RWM, 2016a). There is inevitably a high level of uncertainty relating to the future occurrence of the natural processes evaluated. This is especially true for future phases of glaciation and permafrost activity given the uncertainties surrounding climate change models. To overcome this, it is assumed that the climate change record of the recent geological past (one million years) provides a worst-case scenario of changes that may impact on the depth range of interest. It is not intended to be used, and should not be used, as an indicator of local-scale susceptibility as this may vary markedly across the region. Further assessment will be required to determine local-scale susceptibility.

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

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

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

7.2 GLACIATION

7.2.1 A UK-scale context

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

conditions and over thousands of years, lowland glaciers may, in turn, coalesce to form extensive ice sheets during a continental-scale glaciation (Shaw et al., 2012).

It is clear from the recent geological record that glaciers have been repeatedly active within the UK landscape over the past two and half million years (Clark et al., 2004; Lee et al., 2011). Numerous periods of glaciation have been recognised, although the scale and extent of glaciers have varied considerably. Most glaciations have been comparatively small (i.e. highland glaciations), although some have been more extensive with glaciers expanding into lowland parts of the UK, i.e. lowland glaciations (Clark et al., 2004; Lee et al., 2011). Over the past half a million years, at least two continental-scale glaciations have affected the UK with ice sheets covering parts of lowland UK, on one occasion as far south as the London area (Figure 12; RWM 2016b; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next million years is open to conjecture. This is because the impact 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 view is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK, coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions, means that their occurrence cannot be discounted.

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

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

7.2.2 A regional perspective

Based upon geological evidence, it is widely accepted that the Welsh Borderland region has been glaciated on several occasions during the past two and a half million years (Quaternary Period; see Figure 12); RWM, 2016b; Clark et al., 2004).). During the late Devensian (about 29 000 to 15 000 years ago), adjacent ice caps formed over Wales and coalesced to form a major sector of the last British–Irish ice sheet (Clark et al., 2004). During the peak of glaciation, glaciers extended into the Welsh Borderland region as highland valley and lowland lobes (Loutre and Berger, 2000). This glaciation affected much of northern and central UK and was the second of two known continental-scale glaciations to affect the UK (Loutre and Berger, 2000). Direct evidence for the earlier Anglian Glaciation in the Welsh Borderland region is preserved locally (Loutre and Berger, 2000). However, the position of the Welsh Borderland region relative to a prominent North Atlantic moisture source (the Gulf Stream) and major ice accumulation areas in Wales made it highly susceptible to being glaciated (Clark et al., 2012).

Over the next million years, assuming Britain is glaciated, it is likely that the Welsh Borderland region will experience highland, lowland and continental-scale glaciation (Clark et al., 2012)). This is because its proximity to other ice sources in Wales and the prominent North Atlantic moisture source (the Gulf Stream) make it highly susceptible to glacier inception (Clark et al., 2012). During all scales of glaciation, glacial overdeepening of valleys in marginal highland areas may, over multiple glacial cycles, can cause the localised lowering of the ground surface into the very top of the depth range of interest (c. extending to 200 m), specifically in pre-existing valley areas (RWM, 2016b). The formation of meltwater-incised valleys beneath glaciers (tunnel valleys) in lowland areas of the Welsh Borderland region 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 (RWM, 2016b). Collectively, overdeepening of glacial

valleys and the formation of tunnel valleys can lead to the development of highly localised groundwater behaviour and chemistry (RWM, 2016b). The region may also be affected by isostatic rebound and/or a glacier forebulge during a lowland or continental glaciation affecting an adjacent onshore region (e.g. Wales: RWM, 2016b). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (RWM, 2016b).

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 (see Figure 12) have all been affected by permafrost as indicated by the extensive weathering of surface geological materials (Shaw et al., 2012). Permafrost is important because its presence can affect the subsurface within the depth range of interest by altering groundwater behaviour and chemistry. This is especially the case if the current ground surface has been lowered by glacial erosion (Shaw et al., 2012).

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

7.3.2 A regional perspective

Under future cold climates over the next million years, it is likely that the Welsh Borderland region will be subjected to the development of permafrost to a depth of a few hundred metres (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).
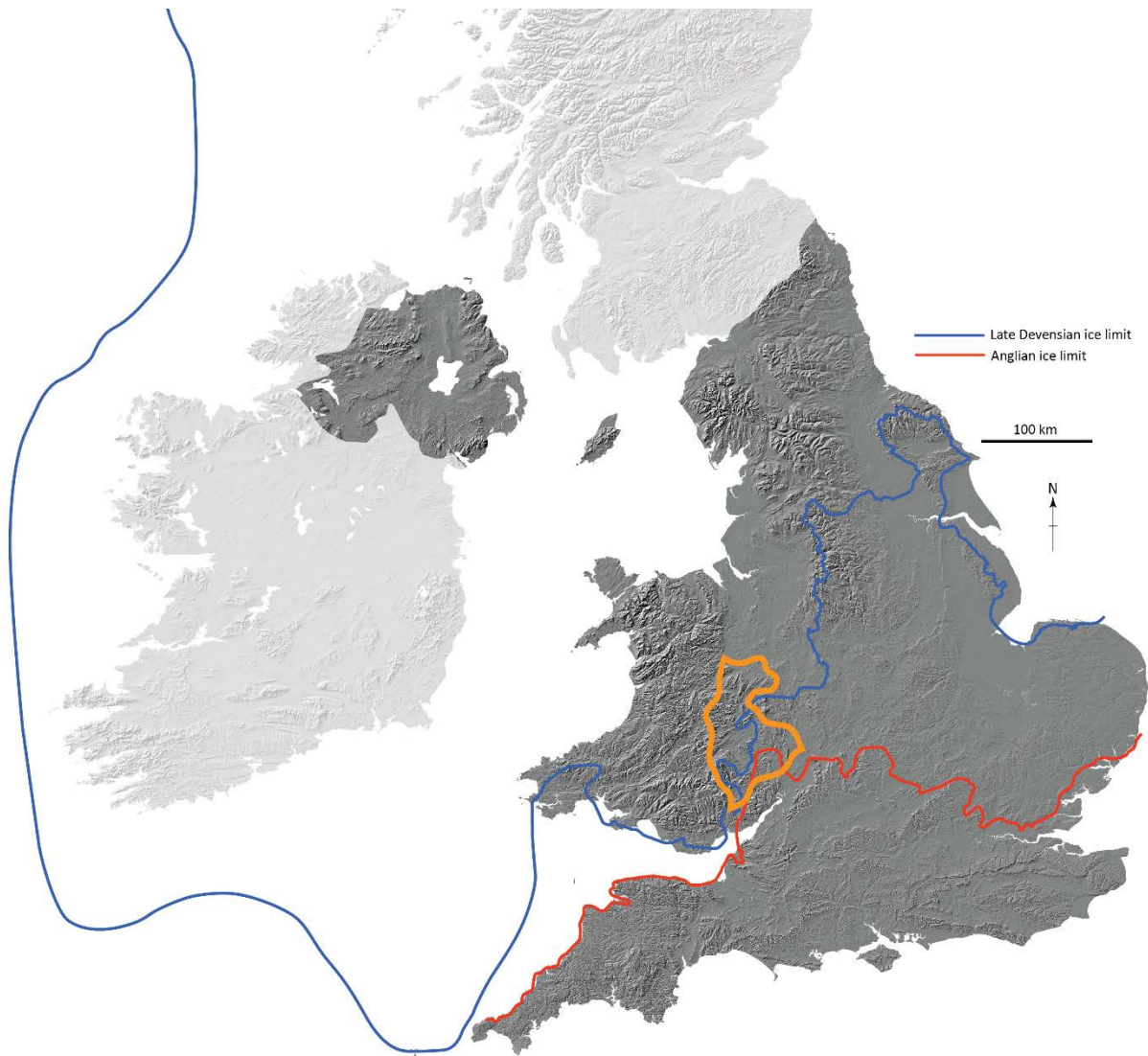
Figure 12 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (approximately 480 to 430 ka) and late Devensian (approximately 30 to 16 ka). The location of the Welsh Borderland region is delineated by the orange line. Produced using Copernicus data and information funded by the European Union — EU-DEM layers ©EEA.

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 13). 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 13). 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).
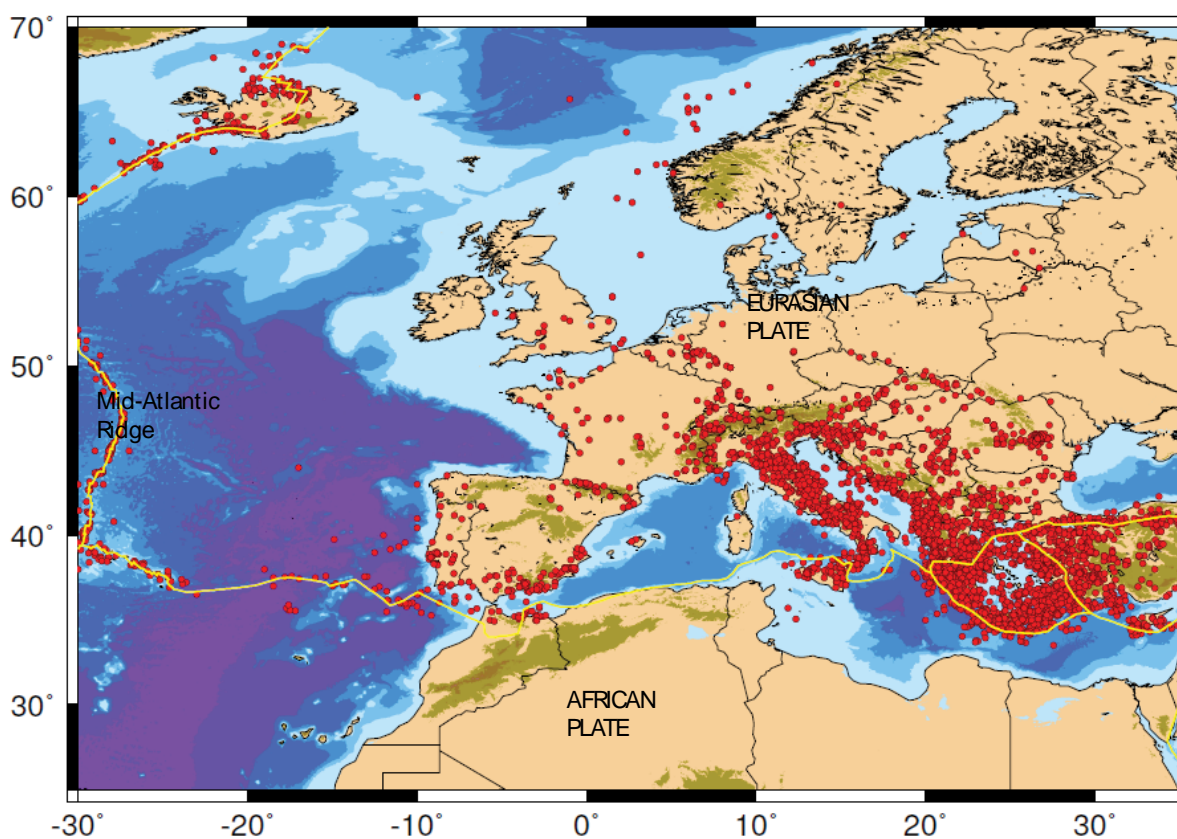

Figure 13 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake Catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

7.4.2   Seismicity catalogue

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

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

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

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

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

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

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

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

A requirement for any statistical analysis of seismicity is that one needs to know the extent to which the record of main shocks in an earthquake catalogue is complete. For example, some historic earthquakes that happened may not be present in the catalogue because no record of them survives to the present day. Normally, completeness improves with time (better nearer the present day) and also with magnitude (better for larger earthquakes). Thus one can describe a series of time intervals within which it is considered that the catalogue definitely contains all earthquakes above a certain magnitude threshold. This threshold value can be defined as the lowest magnitude at which 100 per cent of the earthquakes in a space-time volume are detected (Rydelek and Sacks, 1989). Therefore it is usually low for recent seismicity and gets progressively higher back in time. For this study we use the completeness estimates for the UK catalogue determined by Musson and Sargeant (2007), which are shown in Table 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 14 shows a map of all of the main shocks in the catalogue. The symbols are scaled by magnitude (Mw). It is worth noting that the location uncertainty is ±5 km for instrumental earthquakes and up to ±30 km for historical earthquakes (Musson, 1994). An analysis of the British seismicity clearly shows that it is not correlated with the major tectonic structures that bound the tectonic terranes in the UK (Musson, 2007). The terranes are homogeneous in terms of crustal properties (e.g. distribution and style of faulting), but the seismicity within each block is heterogeneous (Musson, 2007). There are spatial variations in the level of seismic activity across the UK. Western Scotland, western England, Wales, south-western Cornwall and the area off the coast of south-eastern England are the areas of highest activity. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free (Figure 14).

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 14), 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).
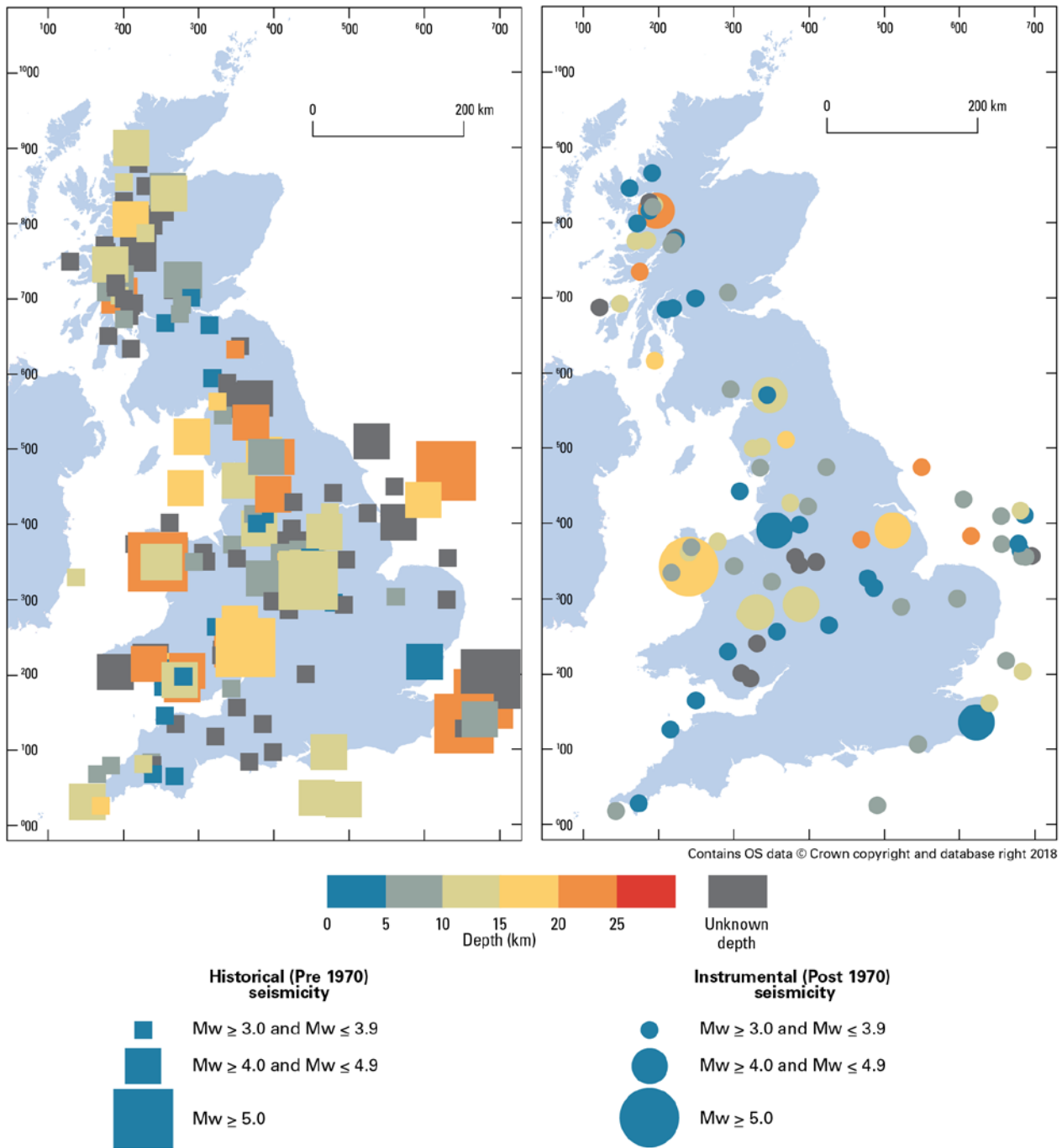
Figure 14 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

7.4.3 Earthquake depths

No earthquake in the UK recorded either historically or instrumentally is known to have produced a surface rupture. Typical fault dimensions for the largest recorded British earthquakes are of the order of 1 to 2 km. Therefore, it is difficult to accurately associate earthquakes with specific faults, particularly at depth, where the fault distributions and orientations are unclear and because of the uncertainties associated with depth estimates. The uncertainties in the focal depths determined for earthquakes are generally large, up to a standard deviation of ±10 km. Figure 15 shows the distribution of focal depths in the catalogue. These are

distributed throughout the crust and the maximum depth in the catalogue is 28 km. This suggests that there is a relatively broad seismogenic zone, i.e. the range of depths in the lithosphere where earthquakes are generated. The larger earthquakes, e.g. the 7 June 1931 Mw 5.9 Dogger Bank earthquake and the 19 July 1984 Mw 5.1 Lleyn earthquake, tend to occur at greater depths (Figure 14).

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.

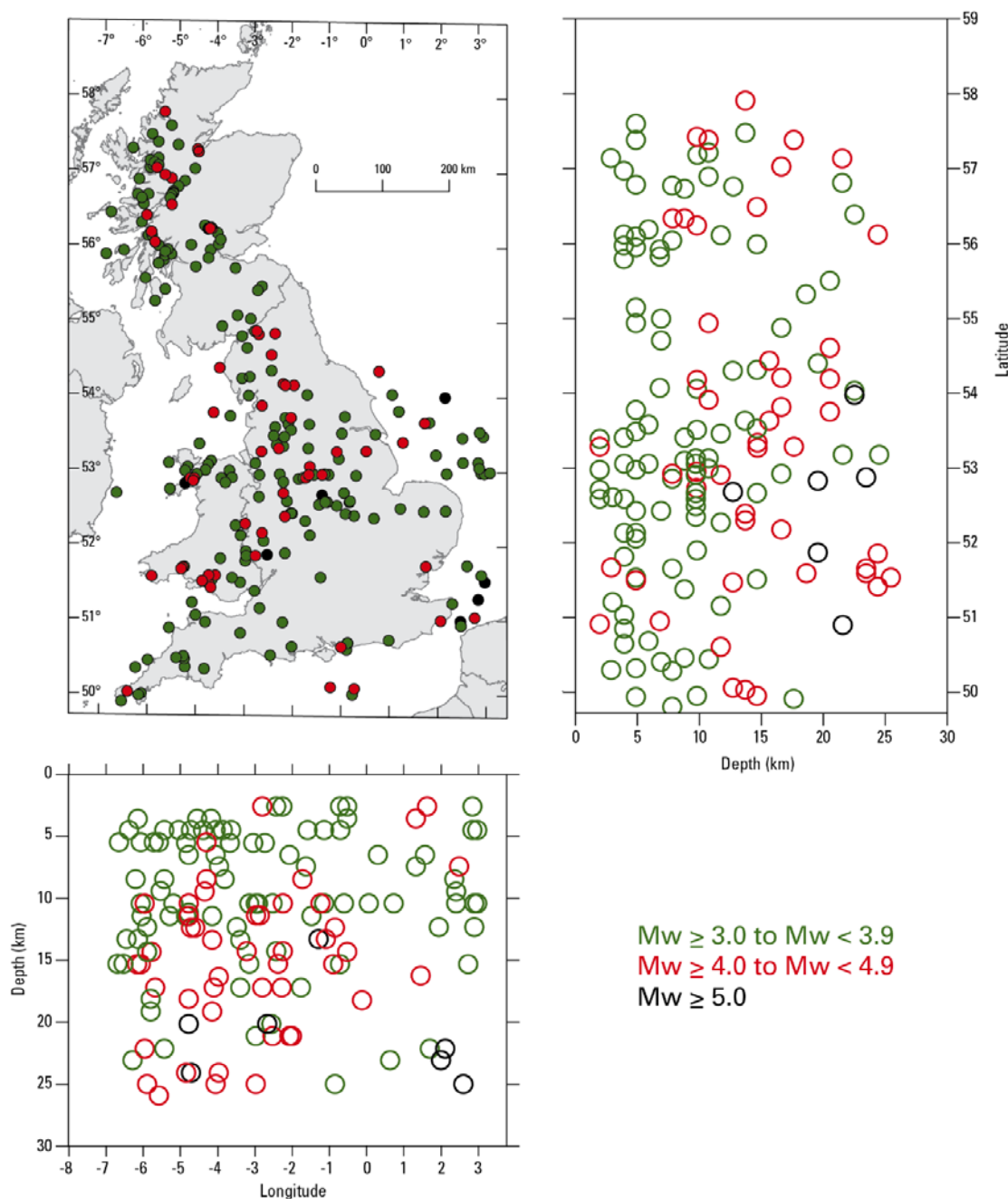**Figure 15** Relationship between the focal depth and the geographical distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

7.4.4 Maximum magnitude

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

The maximum magnitude (Mmax) can be constrained by fault length, i.e. any large earthquake requires a sufficiently large structure to host it, and this certainly limits the locations where great earthquakes (M>8) can occur. In intraplate areas one cannot apply such criteria because there are many examples of strong (Mw 7) earthquakes occurring in virtually aseismic areas (e.g. Johnston et al., 1994). Furthermore, in any low-seismicity area, the length of the seismic cycle may be longer than the historical time window that captures the largest observed possible event (Musson and Sargeant, 2007). For these reasons, maximum magnitude is very much a matter of judgement in an area like the UK. Ambraseys and Jackson (1985) 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 Meghraoui,1996; Camelbeeck, 1999). Therefore, we cannot rule out the occurrence of an earthquake that may have a larger magnitude than the largest magnitude observed in the British seismicity catalogue and may have occurred before the beginning of the historical catalogue.

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

7.4.5 Earthquake activity rates

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

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

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

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

7.4.6 Impact of future glaciation

The possibility of renewed glaciation in the next ten thousand years means that estimates of the distribution and rates of regional seismicity cannot be considered the same as they are now. Geological investigations in a number of regions have found evidence for significant postglacial movement of large neotectonic fault

systems, which were likely to have produced large earthquakes around the end-glacial period. For example, Lagerbäck (1979) suggests that the 150 km long, 13 m high fault scarp of the Pårve Fault in Sweden was caused by a series of postglacial earthquakes. Adams (1996) finds evidence for postglacial thrust faults in eastern Canada. Davenport et al. (1989) and Ringrose et al. (1991) find similar evidence for significant postglacial fault displacements in Scotland. However, Firth and Stewart (2000) argue that these are restricted to metre-scale vertical movements along pre-existing faults.

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

7.4.7 Conclusions

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

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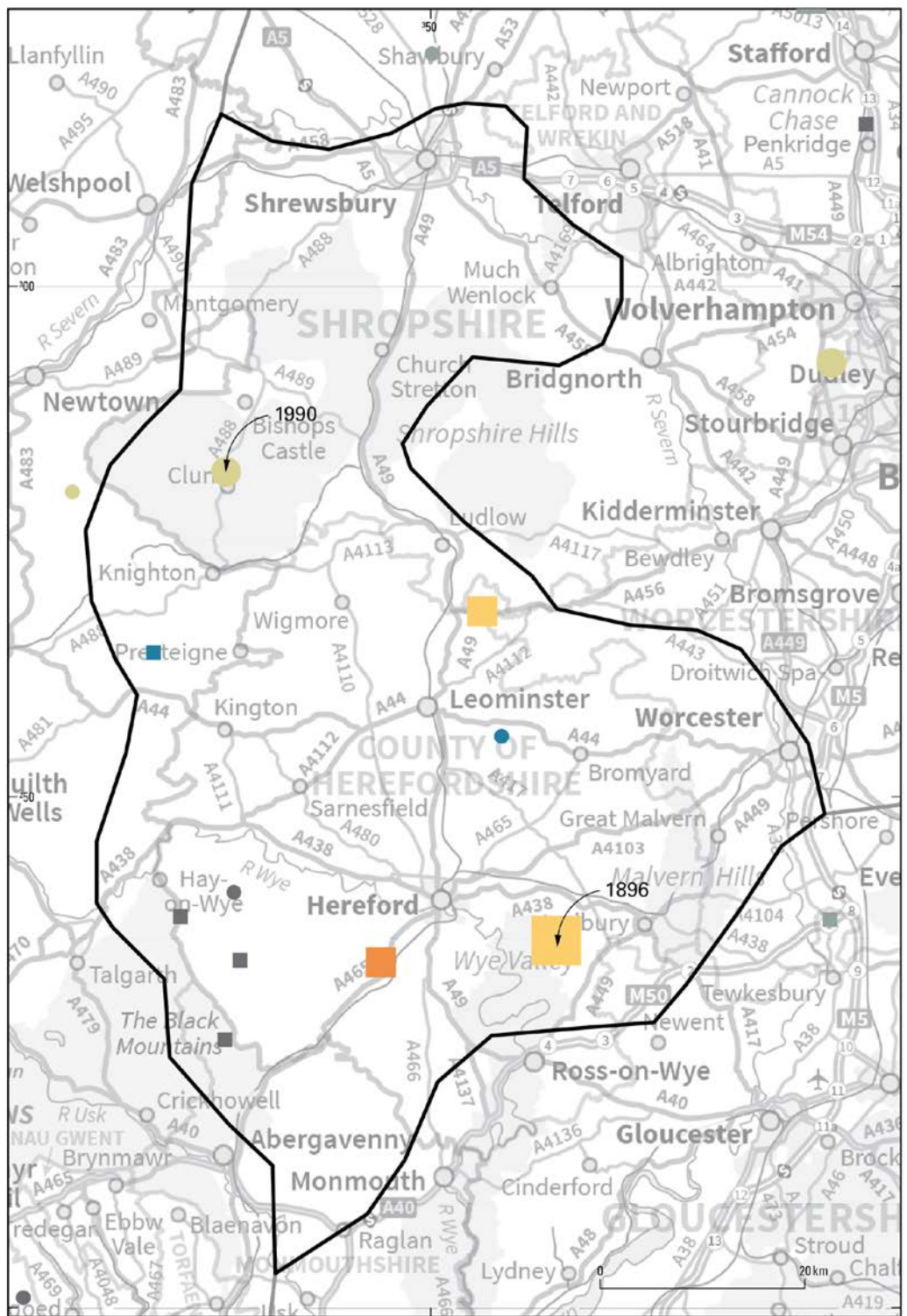
- The duration of the earthquake catalogue (approximately 700 years) is very short compared to the recurrence interval of large earthquakes in intraplate areas (thousands of years) and geological processes (millions of years). As a result, our understanding of earthquakes and earthquake generating processes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

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

7.4.8 A regional perspective

Figure 16 shows earthquake activity in the Welsh Borderland region. This small region has experienced four earthquakes with magnitude of 4.0 Mw or greater in the last 200 years. The largest was a magnitude 5 Mw earthquake in 1896 (Davison, 1899). The epicentre was 6 km east of Hereford and significant damage was caused in Hereford, with damage to the cathedral and other churches, and more than 200 chimneys were damaged (Davison, 1899; Musson, 1994).

More recently, the magnitude 4.8 Mw Bishop's Castle earthquake (Ritchie et al., 1990) was felt over all of Wales and much of England and caused some superficial damage. The distribution of the damage was irregular. In the village of Clun some plaster fell or was cracked, a few chimneys were thrown down, and small damage was reported to the ruins of Clun Castle. At Bishop's Castle there was no damage at all (Ritchie et al., 1990; Musson, 1994).
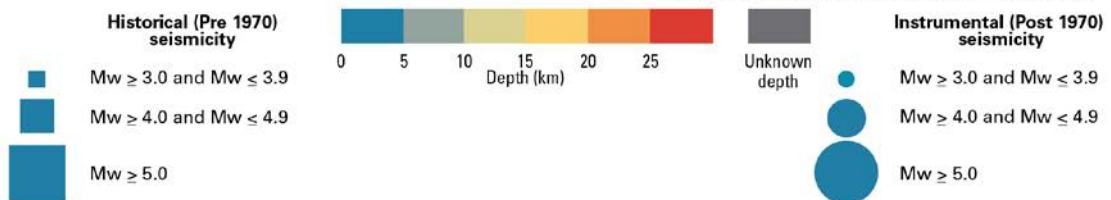
Figure 16 Historical and instrumentally recorded earthquakes in the Welsh Borderland region. The symbols are scaled by magnitude and coloured by depth. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

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8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

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

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

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

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

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

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

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

8.2 OVERVIEW OF RESOURCES IN THE REGION

The distribution of mineral resources in the region is shown in Figure 17. The Welsh Borderland region contains small coalfields that have been mined as well as the Shropshire lead/zinc orefield that has been extensively mined. In the 18th century the Coalport Tar Tunnel was the first (mined) oilfield in the UK.

8.3   COAL AND RELATED COMMODITIES

There are several small coal-bearing areas to the south-west of Shrewsbury and one in the east of the region that have been exploited for coal (Figures 17 and 19)). No mines are now working these areas. The most prospective area (due to its greater extent and higher thickness of coals) is the Coalbrookdale coalfield in the extreme east of the area.

There are no current licences for coal bed methane, coal mine methane, abandoned mine methane or coal gasification in any of the coalfield areas.

8.4   POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

Whilst evaporite deposits occur within the Mercia Mudstone Group in the region, they are not currently worked and are not considered an economic resource.

8.5   OTHER BEDDED AND MISCELLANEOUS COMMODITIES

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

8.6   VEIN-TYPE AND RELATED ORE DEPOSITS

The Shropshire orefield is to the south-west of Shrewsbury (Figures 17 and 19) and has been worked for lead since the Roman occupation and more recently for zinc and barytes. The extent of the Shropshire orefield depicted on Figure 17 delineates where most of the known mineralisation is located, however, large parts of the orefield area is not intensively mineralised and has not been extensively mined or mined to depths exceeding 100 m below NGS datum. Because of the widespread distribution of mineral veins and the extent of past shallow mine workings in the area, the mineral potential may be re-examined in the future.

The last mines closed in the mid-20th century. Several mines worked to depths significantly greater than 100 m below NGS datum, the deepest being Snailbeach Mine that was worked to more than 500 m below NGS datum. Tankerville and Potters Pit mines also reached depths of over 450 m below NGS datum. The mines to the west of the area, such as Roman Gravels, Roundhill and Grit mines were shallower at around 150 m below NGS datum. Between 1845 and 1913, 235 650 tonnes of lead ore were produced from the orefield, along with 18 994 tonnes of zinc ore and 271 397 tonnes of baryte. Metal production rapidly declined in the 20th century but a further 295 108 tonnes of baryte was produced between 1914 and 1944.

8.7   HYDROCARBONS (OIL AND GAS)

There are no conventional hydrocarbon fields in the region and none of the area has been identified as prospective for shale oil or gas. Latent prospectivity for conventional hydrocarbons may exist, as source rocks similar to those of the East Midlands oilfield are present at depth, however, no discovers have been made in exploration boreholes drilled to date.

8.8   GAS STORAGE

There are no planned, under-construction or operating underground gas storage facilities in the region. There seems to be little immediate prospect for underground gas storage, any potential probably lying in lined or unlined caverns in hard rock locations.

8.9   GEOTHERMAL ENERGY

There are no deep geothermal heating systems currently operating in the Welsh Borderland region. Regionally there is little geothermal energy potential in the region because of a lack of large granite intrusions or deep porous sedimentary basins.

8.10   HIGH DENSITY OF DEEP BOREHOLES

There are very few intensively drilled areas in this region. There is one area of deep boreholes (greater than 200 m below NGS datum) with a density of two boreholes per square kilometre north of Great Malvern which have been drilled for site investigation for infrastructure projects.

8.11   SUPPORTING INFORMATION

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

Reported mine depths are often difficult to attribute to specific datums. 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(s) 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 given adits were typically driven from nearby valleys. This is assuming 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 over-estimate of actual depth.

8.11.1   Mined extents

The areas of vein-type and related ore deposits shown on Figure 17 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.
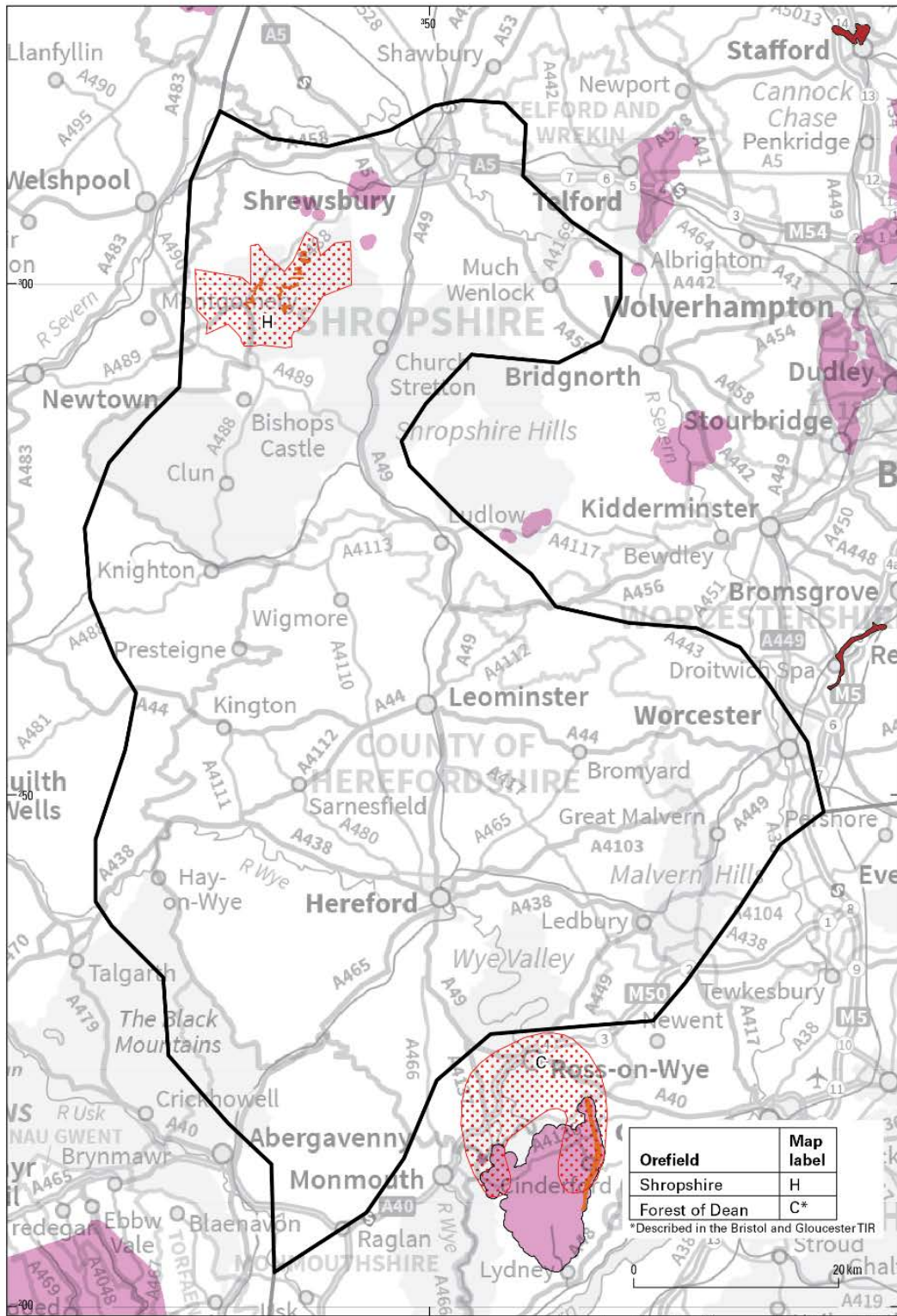
Figure 17 Distribution of mineral resources in the Welsh Borderland region. Depleted oil and gas fields and underground gas storage licence areas are not shown. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

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Figure 18 Location of intensely drilled areas in the Welsh Borderland region, showing the number of boreholes drilled per 1 km² that penetrate greater than 200 m below NGS datum. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.

Figure 19 Distribution of coal resources in the Welsh Borderland region. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018.
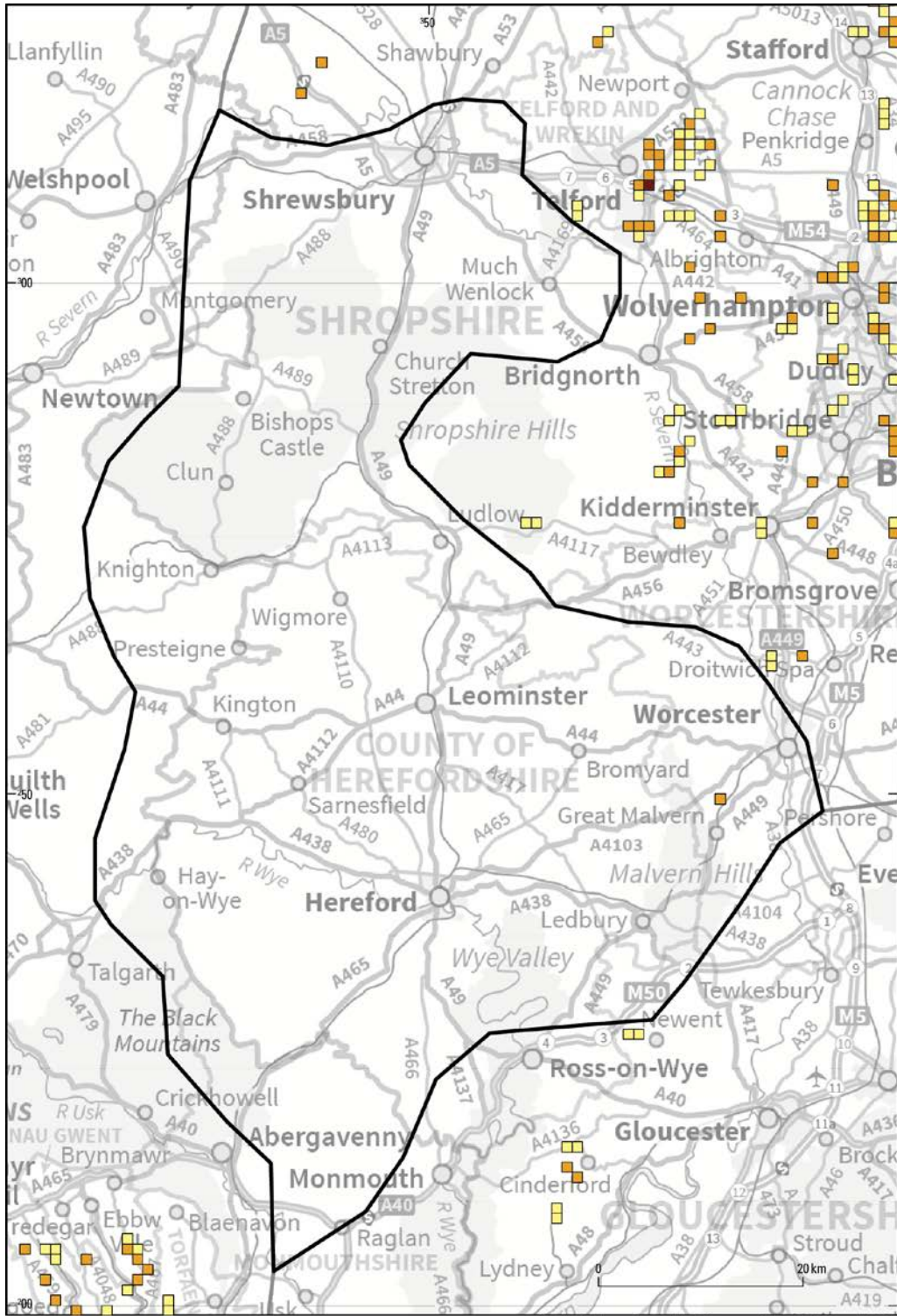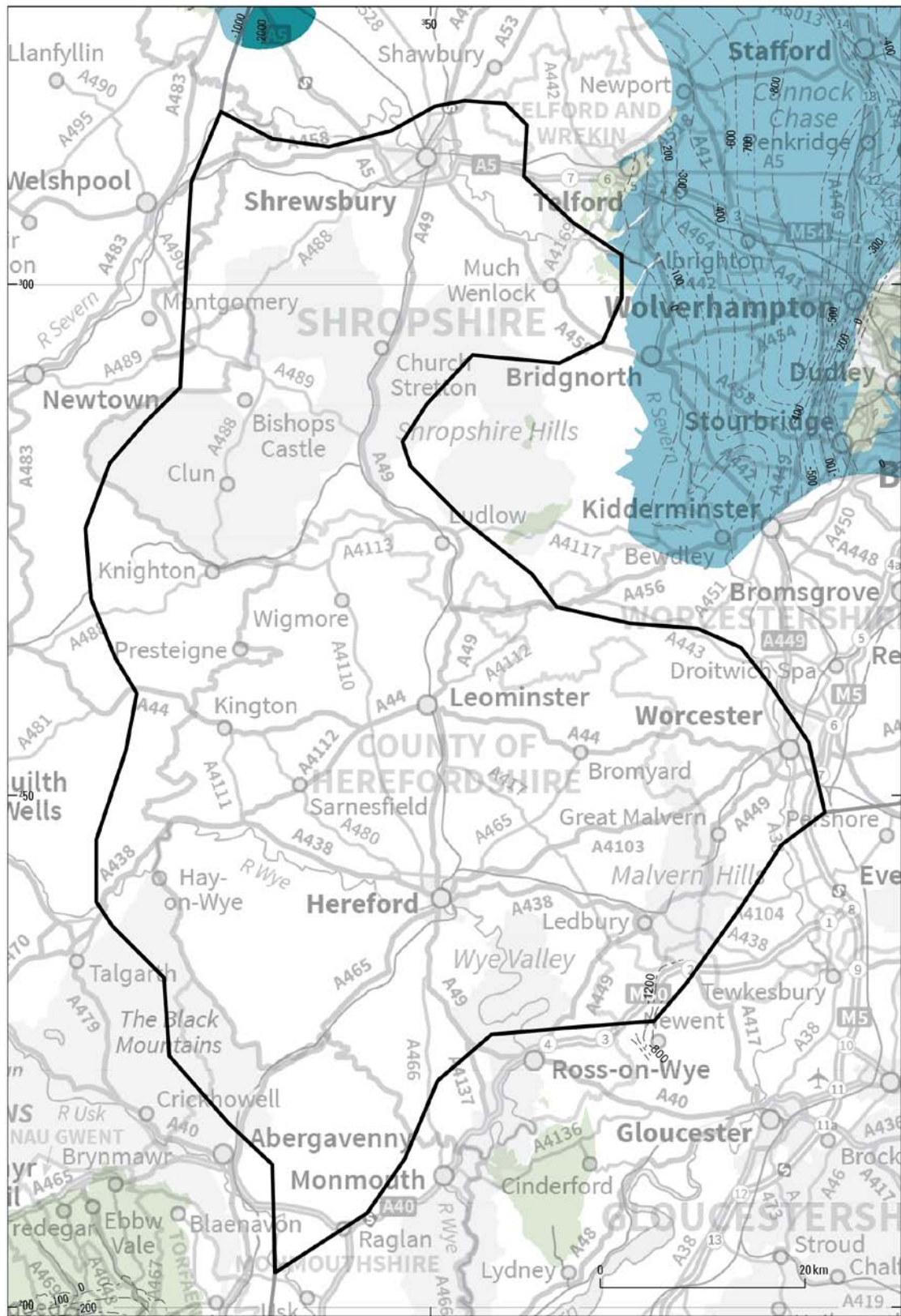
8.11.2 Coal and related commodities

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

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

8.11.3 Borehole depths

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

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

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

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Hydrocarbon resources

The locations of onshore 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/