National Geological Screening: Northern Ireland

Minerals and Waste Programme

Commissioned Report CR/17/096

BRITISH GEOLOGICAL SURVEY

MINERALS AND WASTE PROGRAMME

COMMISSIONED REPORT CR/17/96

National Geological Screening: Northern Ireland

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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 Northern Ireland to underpin its 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, 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 Northern Ireland (Figure 1).

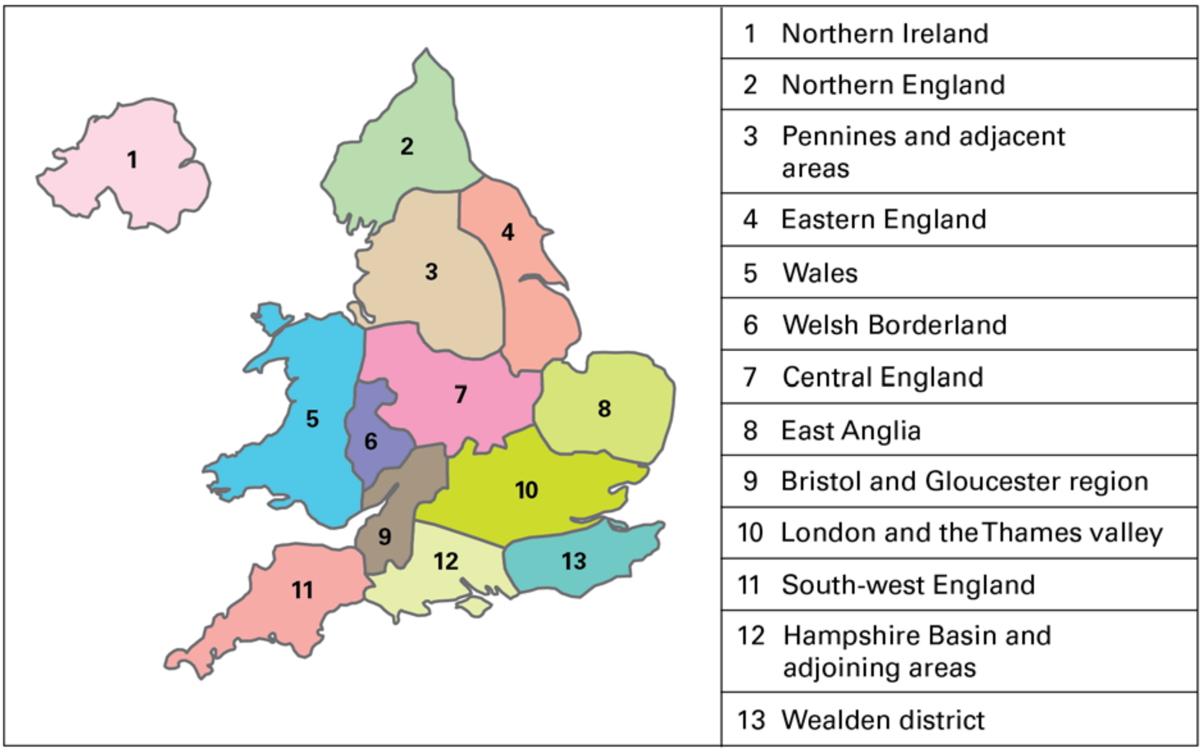


Figure 1 The BGS region boundaries as defined by the Regional Guides series of reports (see http://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html). British Geological Survey © UKRI 2018

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

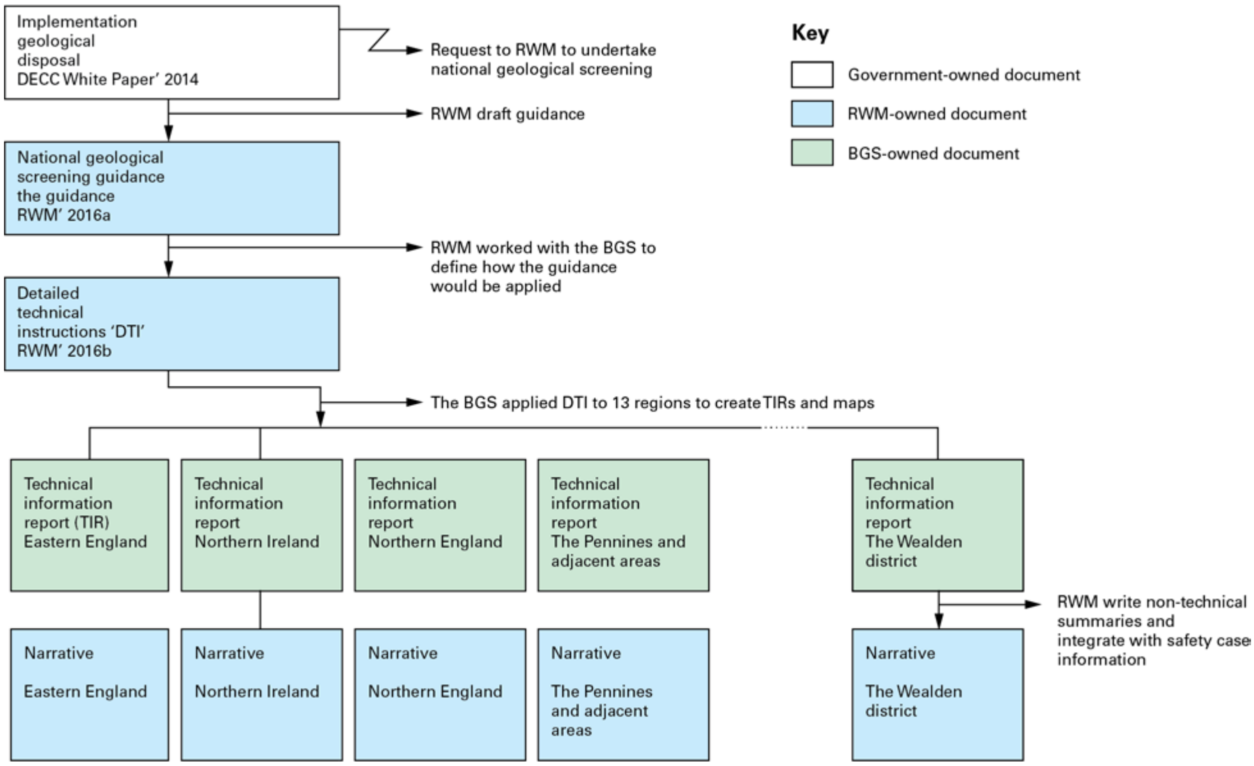


Figure 2 Schematic diagram of the national geological screening process and arising documents.

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, including an element of flexibility to take account of variations in data availability and quality. The DTIs are specific to each of the five geological topics: rock type, rock structure, groundwater, natural processes and resources. For each, the DTI sets out a step-by-step description of how to produce each output including how the data and information related to the topic will be assembled and presented to produce the TIRs and any associated maps required by the guidance. Specifically, for each topic, the DTI describes:

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

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

2.3 TECHNICAL INFORMATION REPORTS AND MAPS

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

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

i. **Rock type**

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

ii. **Rock structure**

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

iii. **Groundwater**

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

iv. **Natural processes**

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

v. **Resources**

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

3 Northern Ireland

Northern Ireland covers an area of about 14 000 km^2, and includes counties Tyrone, Londonderry, Antrim, Down, Armagh and Fermanagh **(**Figure 3). It shares a border with the Republic of Ireland. The landscape of Northern Ireland is remarkably varied considering its relatively small area and this is a reflection of the diverse geology on which it has been shaped (GSNI, 1997; Mitchell, 2004).

Much of the surface geology of the province has been surveyed in great detail and can be examined in numerous quarries, stream and coastal exposures of rock. A large number of shallow boreholes, though mainly in urban areas, also provide information on the near-surface geology. Insight into the deeper geology is provided through a collection of about 45 deep boreholes, with depths greater than 200 m, drilled across Northern Ireland during the last 40 years or so, in search of hydrocarbons, minerals and geothermal resources. A recent geophysical survey (Young and Donald, 2013), referred to as the Tellus Project, has provided new, high-resolution geophysical data that reveal patterns of the Earth's magnetic and electromagnetic properties. Understanding these patterns, when combined with geophysical seismic data, obtained by sending sound waves through the ground and with gravity data, allows interpretation of the geological structure to a depth of several kilometres.

3.1 OVERVIEW OF THE GEOLOGY OF NORTHERN IRELAND

The geology at surface 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 Northern Ireland 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.

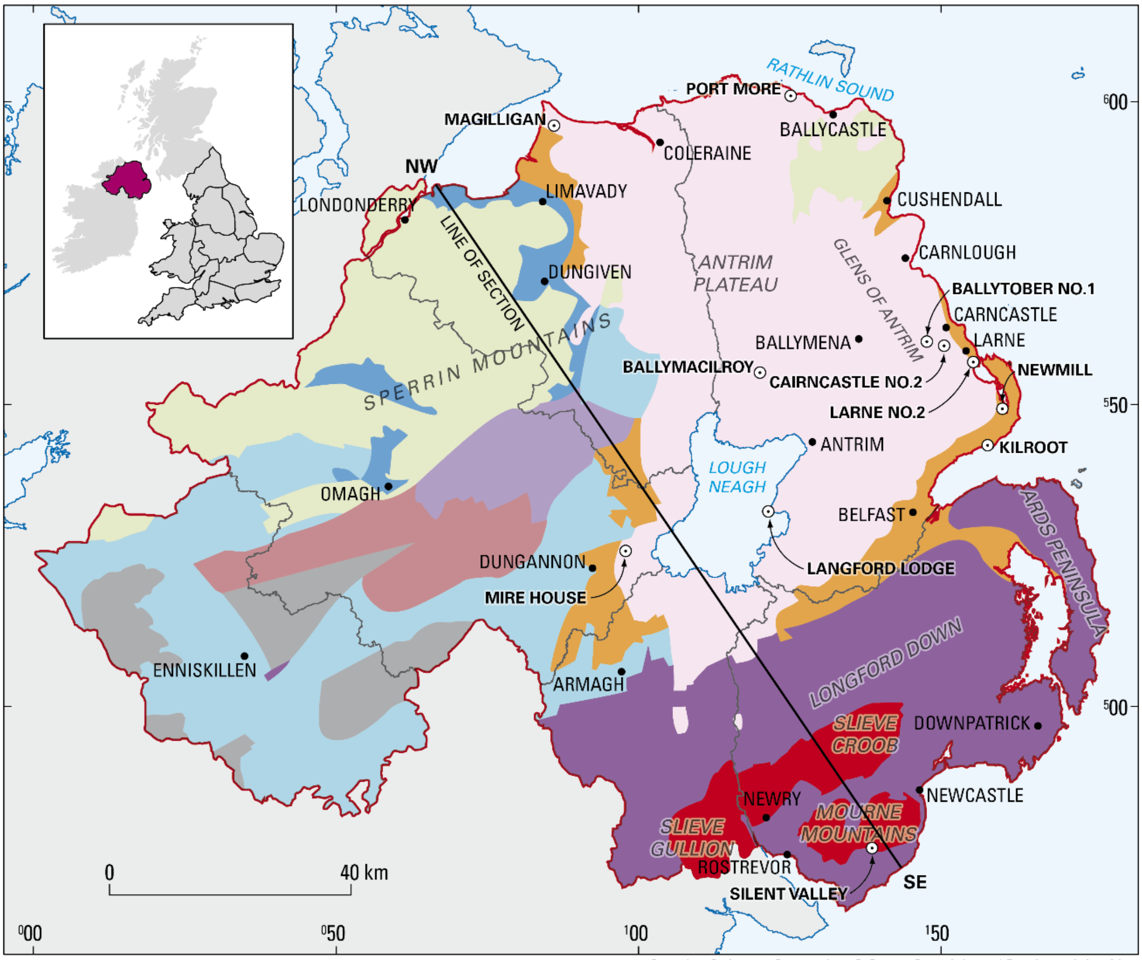
In broad terms the geology of Northern Ireland, summarised in Figures 3 and 4, can be divided into four contrasting areas.

In the north-west the oldest rocks within the region are Precambrian and Ordovician in age and form the Sperrin Mountains and their foothills, positioned between Londonderry and Omagh and extending east towards Limavady.

The second area forms the south-east of the region and is positioned between Armagh and Belfast in the north-west and north-east respectively, and Newry and Downpatrick in the south-west and south-east respectively. It is known as the Longford–Down terrane and is composed of Ordovician to Silurian rocks.

In the south-west of the region, the third area is composed of rocks of Devonian and Carboniferous age that are situated between Omagh in the north, Enniskillen in the west and Dungannon and Armagh in the east.

The fourth and youngest area known as the Antrim Plateau lies in the north-east of the region. The plateau is located between Limavady and Ballycastle in the north-west and north-east and Armagh and Larne in the south-west and south-east respectively. The Antrim Plateau is dominated by rocks ranging in age from Permian to Oligocene and includes Lough Neagh, the largest lake on the Island of Ireland. The older rocks of Area 1 continue under these younger rocks of the Antrim Plateau and crop out in Co. Antrim between Ballycastle and Cushendall, where they form the north-east Antrim Inlier.



Age (Ma)	Map/Section descriptor	Geological sub-units	Text descriptor
55–60	Palaeogene	Mourne Mountains Complex	Younger sedimentary rocks, granites and lavas
		Antrim Lava Group	
70–300	Cretaceous to Permian sedimentary rocks	Chalk and Lias groups Mercia Mudstone, Sherwood Sandstone and Belfast groups	
300–345	Carboniferous sedimentary rocks	Coal Measures Group Millstone Grit Group	Older sedimentary rocks and granites
		Carboniferous Limestone and mudstones (Tyrone Group)	
		Roe Valley Group	
360–415	Devonian sedimentary rocks	Fintona and Cross Slieve groups	
		Newry Igneous Complex	
430–460	Silurian and Ordovician	Hawick and Gala groups and Leadhills Supergroup	Basement rocks
465–650	Ordovician–Precambrian	Tyrone Volcanic Group	
		Daldradian and Moine supergroups	

Figure 3 Generalised geological map and key showing the distribution of younger sedimentary rocks, granites and lavas, older sedimentary rocks and granites, and basement rocks in onshore Northern Ireland. The inset map shows the extent of Northern Ireland 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 Northern Ireland. Stratigraphical nomenclature and lithological descriptions are simplified and therefore may differ from those used in other sections of this report. The locations of key boreholes mentioned in the text are shown by a circle and dot. Contains Ordnance Data © Crown Copyright and database rights 2018 Ordnance Survey Licence no. 100021290. British Geological Survey © UKRI 2018.

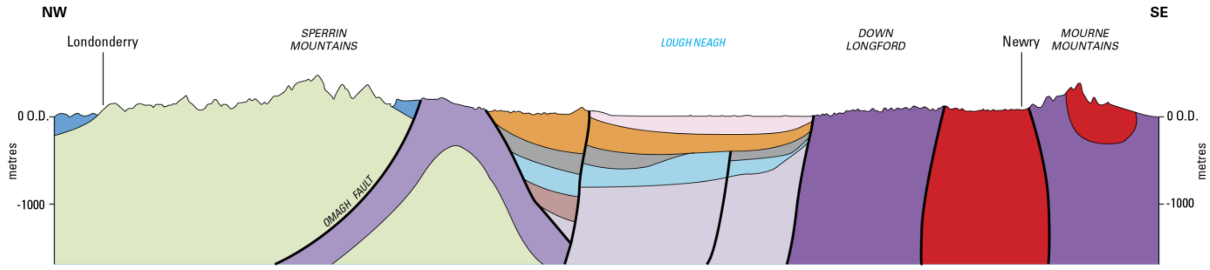


Figure 4 Schematic north-west to south-east cross-section through Northern Ireland. Line of the section and key are shown in Figure 3. British Geological Survey © UKRI 2018

4 Screening topic 1: rock type

4.1 OVERVIEW OF THE ROCK TYPE APPROACH

The rock type DTI (RWM, 2016b) sets out how data and information on the topic of rock type are assembled and presented to produce maps for each region showing the distribution of potential host rocks at 200 to1000 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 which 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 potential 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 NORTHERN IRELAND

Table 3 presents a generalised vertical section (GVS) for Northern Ireland 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 Northern Ireland, the GVS (Table 3) groups the rocks into three age ranges:

- younger granites, lavas and sedimentary rocks (Palaeogene to Permian)
- older sedimentary rocks and older granites (Carboniferous and Devonian)
- basement rocks (early Palaeozoic and older).

Some of the rock units are considered to represent PRTIs present within the depth range of interest, from 200 to 1000 m below NGS datum and are listed in Table 3. These include a number of lower strength sedimentary rock units (LSSR), as well as evaporites (halite) and higher strength rock (HSR) units. Some of the PRTI units are considered together in instances where they form related geological sequences and/or where the units occur undivided in the NGS3D national model.

The following units have been excluded as PRTIs and are thus not described below or shown on the map accompanying this report for the following reasons:

1. The Palaeogene Antrim Lava Group are not included as PRTIs on the basis that, although predominantly basaltic, the rock unit comprises a series of lava flows with variable thickness and strength and the flow tops and bottoms are generally rotten and the centres of flows are fresh.
2. Belfast Group interbedded sandstones, mudstones, and limestones are not included on the basis of their lithological complexity and are therefore unsuitable to be considered as a LSSR.
3. Silurian rocks of the Longford–Down area are highly tectonised, altered sandstone (greywacke) dominated with lesser siltstone and mudstone and therefore are lithologically complex. Mudstone units within these packages, such as the Moffat Shales, are steeply dipping and thin (tens of metres thick), broken and imbricated by faulting and invariably surrounded by sandstone beds. On that basis they have not been considered further.
4. Similarly, the following HSR type rocks have been excluded as they are too structurally and lithologically complex: unnamed mafic igneous intrusions of Ordovician and Silurian age; unnamed Ordovician extrusive rocks.
5. Unnamed extrusive Silurian to Devonian felsic lavas and tuffs are not identified as PRTIs on the basis of their limited extent and they are only currently known to occur at surface in County Tyrone.

The PRTIs are described below 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 they vary across Northern Ireland are also summarised. Data are taken from a range of sources including Mitchell (2004) and other published sources (see references). They may include terminology or nomenclature that has been updated since those publications were released. The term ‘mudstone’ follows BGS usage to include claystone and siltstone grade siliciclastics (Hallsworth and Knox, 1999). The locations of boreholes referred to in this chapter are shown on Figure 3.

Three maps showing the regional distribution of PRTIs between 200 and 1000 m below NGS datum for the three generic host rock types are provided in Figures 5, 6 and 7. A summary map showing the combined distribution of all PRTIs is provided in Figure 8.

Table 3 Schematic GVS for Northern Ireland 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 type (i.e. LSSR, EVAP and HSR respectively).

Geological period		Geological unit identified in NGS3D	Dominant rock type	Potential rock types of interest			Principal aquifers (within geological unit)
				HSR	LSSR	EVAP	
YOUNGER SEDIMENTARY ROCKS, GRANITES AND LAVAS	Palaeogene	Unnamed igneous intrusion and extrusives	Dolerite and gabbro, basalt	Named and unnamed sills—Rathlin Island only	N/A	N/A	N/A
		Unnamed igneous intrusion	Granite	Mourne Mountains Complex	N/A	N/A	N/A
	Cretaceous	Ulster White Limestone Formation	Chalk (compacted)	N/A	N/A	N/A	Ulster White Limestone Formation
		Hibernian Greensands Formation	Sandstone, siltstone and claystone	N/A	N/A	N/A	Hibernian Greensands Formation
	Jurassic	Lias Group	Claystone, siltstone, limestone and sandstone	N/A	Waterloo Mudstone Formation	N/A	N/A
	Triassic	Mercia Mudstone Group and Penarth Group (undivided)	Claystone, siltstone and sandstone with evaporite deposits of halite	N/A	Mercia Mudstone Group and Penarth Group (undivided)	Ballyboley, Carnduff and Larne halites	N/A
		Sherwood Sandstone Group	Sandstone, siltstone and claystone	N/A	N/A	N/A	Sherwood Sandstone Group
	Permian	Belfast Group	Limestone, mudstone, sandstone and siltstone	N/A	N/A	N/A	
		Enler Group	Sandstone, breccia, siltstone and claystone	N/A	N/A	N/A	Enler Group
OLDER SEDIMENTARY ROCKS, INCLUDING GRANITES	Carboniferous	Coal Measures Group, Millstone Grit Group	Sandstone, siltstone, claystone and coal	N/A	N/A	N/A	N/A
		Tyrone Group	Limestone and mudstone	N/A	N/A	N/A	Glencar, Dartry, Ballyshannon Limestone Ballysteen, Ulster Coal, Cooldargh and Fearnaght formations
		Roe Valley Group	Interbedded claystones, limestones, siltstones	N/A	N/A	N/A	N/A
	Devonian	Flintona and Cross Slieve groups	Sandstone, conglomerate and minor mudstone	N/A	N/A	N/A	N/A
		Unnamed igneous intrusion	Granodiorite and granite	Newry Igneous Complex	N/A	N/A	N/A
BASEMENT ROCKS	Silurian	Hawick and Gala groups	Altered lithic sandstones	N/A	N/A	N/A	N/A
	Ordovician	Leadhills Supergroup	Altered lithic sandstones	N/A	N/A	N/A	N/A
		Unnamed igneous intrusion—felsic rock	Granite	Tyrone Igneous Complex	N/A	N/A	N/A
	Neoproterozoic	Dalradian Supergroup	Psammite, quartzite, semipelite, pelite, limestone and metamorphosed basic igneous rocks	Argyll and Southern Highlands groups	N/A	N/A	N/A
		Moine Supergroup—Tyrone central inlier and Lough Derg Group	Psammite and semipelite	Tyrone central inlier and Lough Derg Group	N/A	N/A	N/A

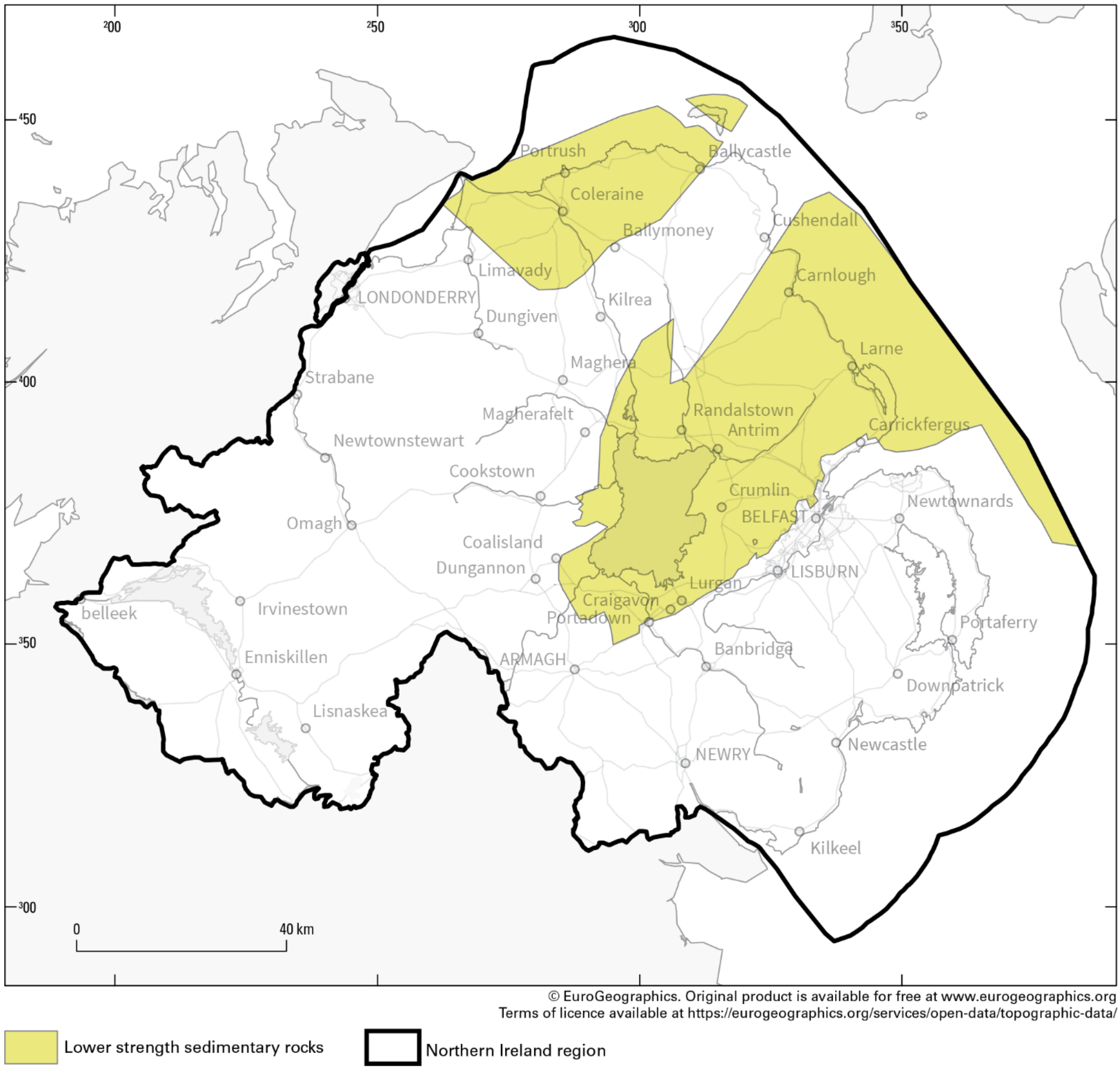


Figure 5 The generalised lateral distribution of LSSR PRTIs at depths of between 200 and 1000 m below NGS datum in in Northern Ireland. Contains EuroGeographics data ©EuroGeographics. Contains British Geological Survey digital data © UKRI 2018

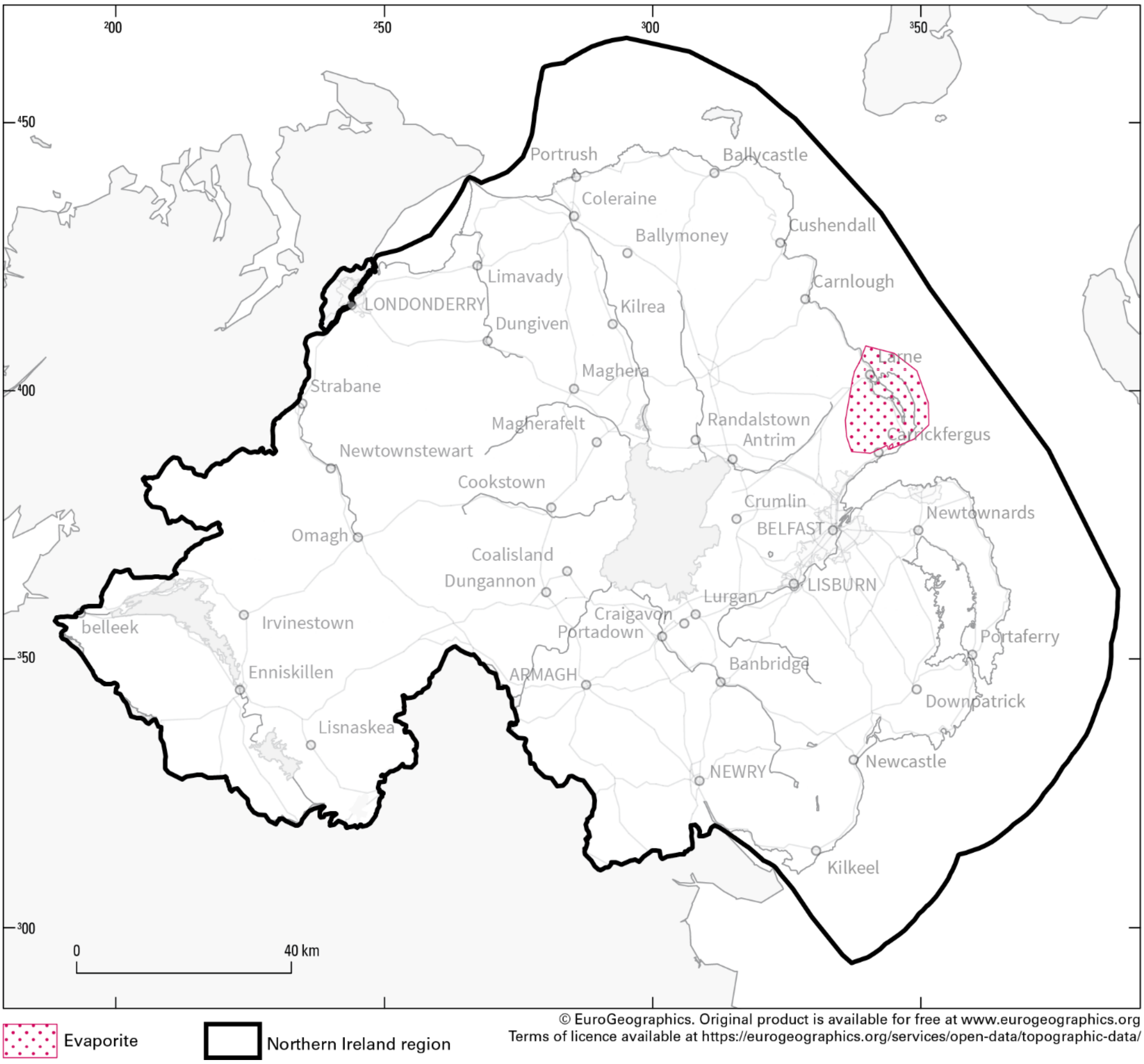


Figure 6 The generalised lateral distribution of EVAP PRTIs at depths of between 200 and 1000 m below NGS datum in Northern Ireland. Contains EuroGeographics data ©EuroGeographics. Contains British Geological Survey digital data © UKRI 2018

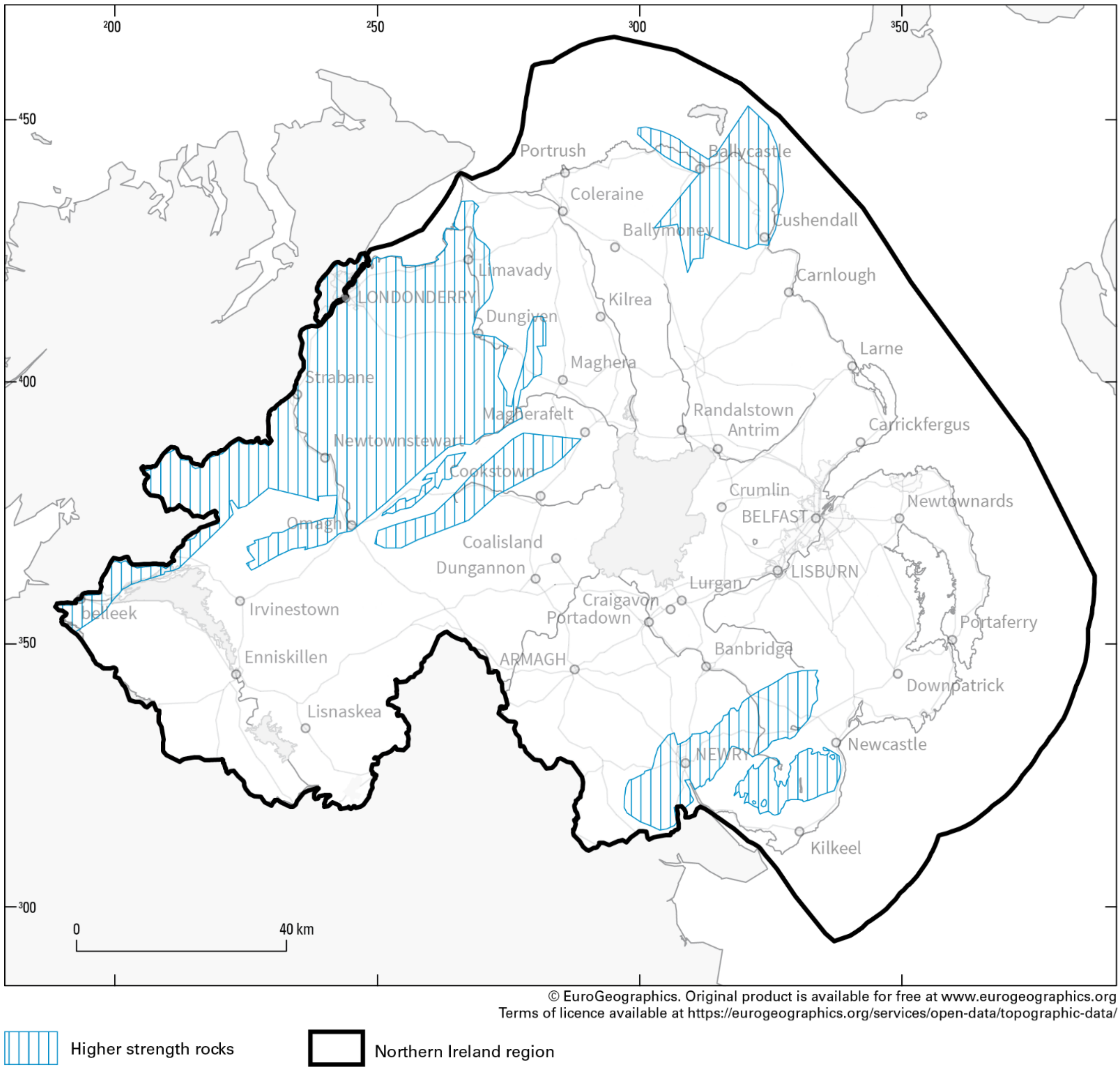


Figure 7 The generalised lateral distribution of HSR PRTIs at depths of between 200 and 1000 m below NGS datum in Northern Ireland. Contains EuroGeographics data ©EuroGeographics. Contains British Geological Survey digital data © UKRI 2018

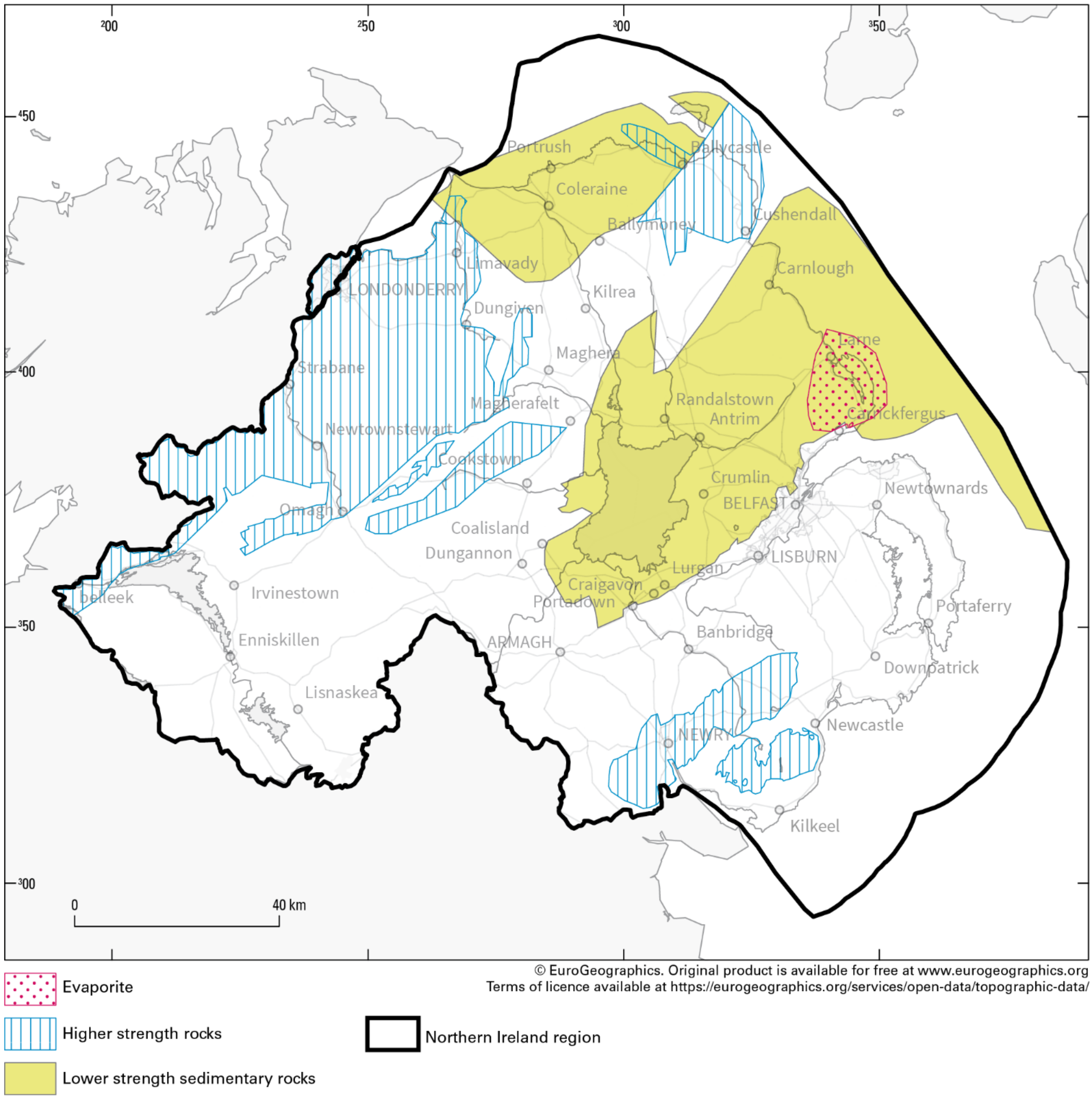


Figure 8 The generalised combined lateral distribution of LSSR, EVAP and HSR PRTIs at depths of between 200 and 1000 m below NGS datum in Northern Ireland. Contains EuroGeographics data ©EuroGeographics. Contains British Geological Survey digital data © UKRI 2018

4.2.1 Younger granites, lavas and sedimentary rock PRTIs

4.2.1.1 Unnamed Palaeogene igneous intrusion: mafic igneous rock — HSR

Palaeogene sills and sill complexes occur within the Permian to Palaeogene rocks of Northern Ireland, associated with the Antrim Plateau and its margins. The majority of the sills however are of insufficient volume to be considered as PRTIs. However, sills have also been recorded within offshore basins, and are particularly numerous in the Rathlin basin located north of Coleraine and Ballycastle where they may reach thicknesses and depths sufficient to be considered as PRTIs.

Principal information sources

A sill with a drilled thickness just over 220 m was encountered west of Ballycastle in the Port More Borehole (Figure 3) (Wilson and Manning, 1978) within the depth range of interest. The lateral extent of the Port More sill has been revealed by the Tellus Project magnetic imagery (Young and Donald, 2013), which shows two elliptical bodies (10 by 5 km diameter) immediately offshore of Ballycastle. The sill extends inland from the Port More borehole up to where it meets the Tow Valley Fault, and occurs within the depth range of interest. The sill is positioned above the Mercia Mudstone Group.

Rock type descriptions

Palaeogene sills are exclusively basic igneous intrusives and composed of dolerite and gabbro with some basalt. The Port More Sill is composed mainly of medium to coarse-grained dolerite with fine-grained basalt at its upper and lower contacts. The rocks of this sill have cooling joints orientated parallel and perpendicular to the upper and lower contacts. There are also zones within the sill that are described as being vesicular and amygdaloidal (mineral-filled former gas bubbles).

4.2.1.2 UNNAMED PALAEOGENE IGNEOUS INTRUSION: FELSIC IGNEOUS ROCK — HSR

This unit refers to granites of Palaeogene age from the Mourne Mountains in County Down between Rostrevor in the west and Newcastle in the east (Figure 3). They occur as two separate parts known as the Eastern Mournes Centre and Western Mournes Centre (Mitchell, 2004).

Principal information sources

Detailed mapping of the two centres was completed by Queen’s University Belfast research students between 1981 and 1984 and has been published (Mitchell, 2004). These maps provide the best understanding of the granite types and their distribution. Total thickness of the Mourne Mountains Complex is uncertain, however a borehole located in Silent Valley encountered about 600 m of granite before terminating.

Rock type descriptions

The Mourne granites are subdivided into five main types (G1–G5) depending on subtle variations in grain size and composition (Mitchell, 2004). The Eastern Mournes Centre includes G1–G3 granites whilst the Western Mournes Centre hosts G4 and G5. The granites tend to be fine to coarse grained and are cut by cooling and other joint surfaces.

4.2.1.3 LIAS GROUP: MUDSTONE, SILTSTONE, LIMESTONE AND SANDSTONE — LSSR

Rocks of the Jurassic Lias Group in Northern Ireland are restricted to the vicinity of the Antrim Plateau and its margins, located between Limavady and Ballycastle in the north-west and north-east and Armagh and Larne in the south-west and south-east respectively (Figure 3). The thickest Lias Group rocks occur in relatively restricted areas known as sedimentary basins. These include the Rathlin and Foyle basins in north County Antrim and County Londonderry, the Larne basin in east County Antrim and the Lough Neagh basin in south-west County Antrim and north County Armagh (Figure 9). The Lias Group is composed of rocks of the Early Jurassic Waterloo Mudstone Formation which is a potential LSSR PRTI.

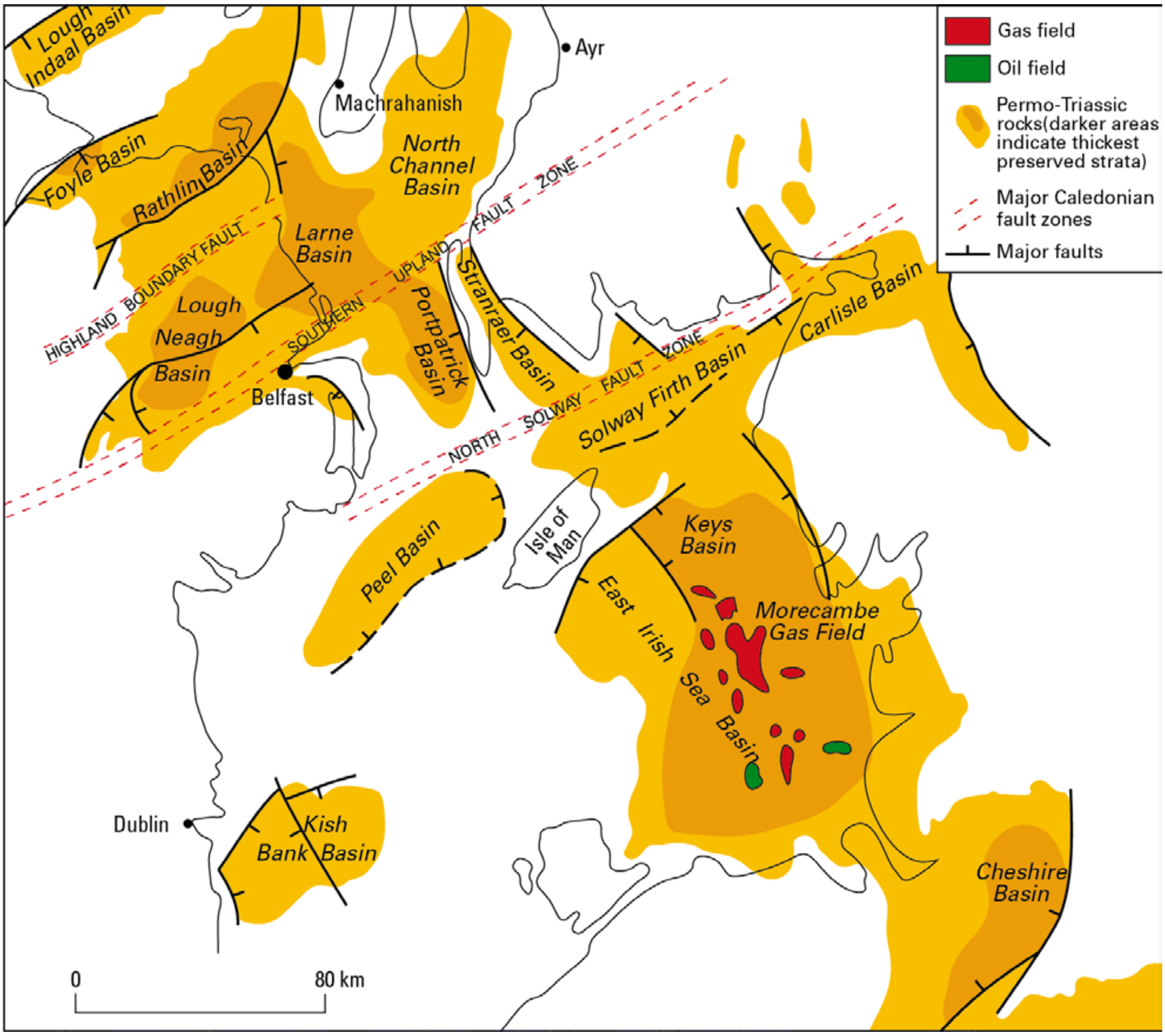


Figure 9 Sedimentary basins across Northern Ireland (from Mitchell, 2004, Fig. 17.1). Geological Survey of Northern Ireland,© Crown Copyright.

Principal information sources

In Northern Ireland, the Lias Group tends to be poorly exposed at surface. However, at the Waterloo coastal section near Larne, which extends for about 500 m, there is an almost complete rock exposure of the sequence (Mitchell 2004).

The distribution of Lias Group at depth is known from a number of hydrocarbon exploration boreholes and geophysical seismic profiles (Figure 10; Mitchell, 2004). In the Rathlin basin the Lias Group was penetrated by the Port More borehole and was shown to be approximately 250 m thick and within the depth range of interest. Farther west in the Foyle basin only the basal 70 m (approximately) of the Lias Group was encountered at surface in the Magilligan Borehole, but appears to be gently inclined inland according to the UK3D model (Waters et al., 2015) and may extend from this borehole location east to the Port More Borehole (Figure 10). To the south of the Rathlin basin the extent of Lias Group rocks is bounded by the Tow Valley Fault and a ridge of older rocks, known as the Highland Border ridge, that run from Dungiven in the south-west to Ballycastle in the north-east, and separate these northern basins from the Larne and Lough Neagh basins (Figure 10). Boreholes that have encountered the Lias Group in the Larne basin include Ballytober No. 1 and Cairncastle No. 2 however at both localities the rocks were shallower than the depth range of interest.

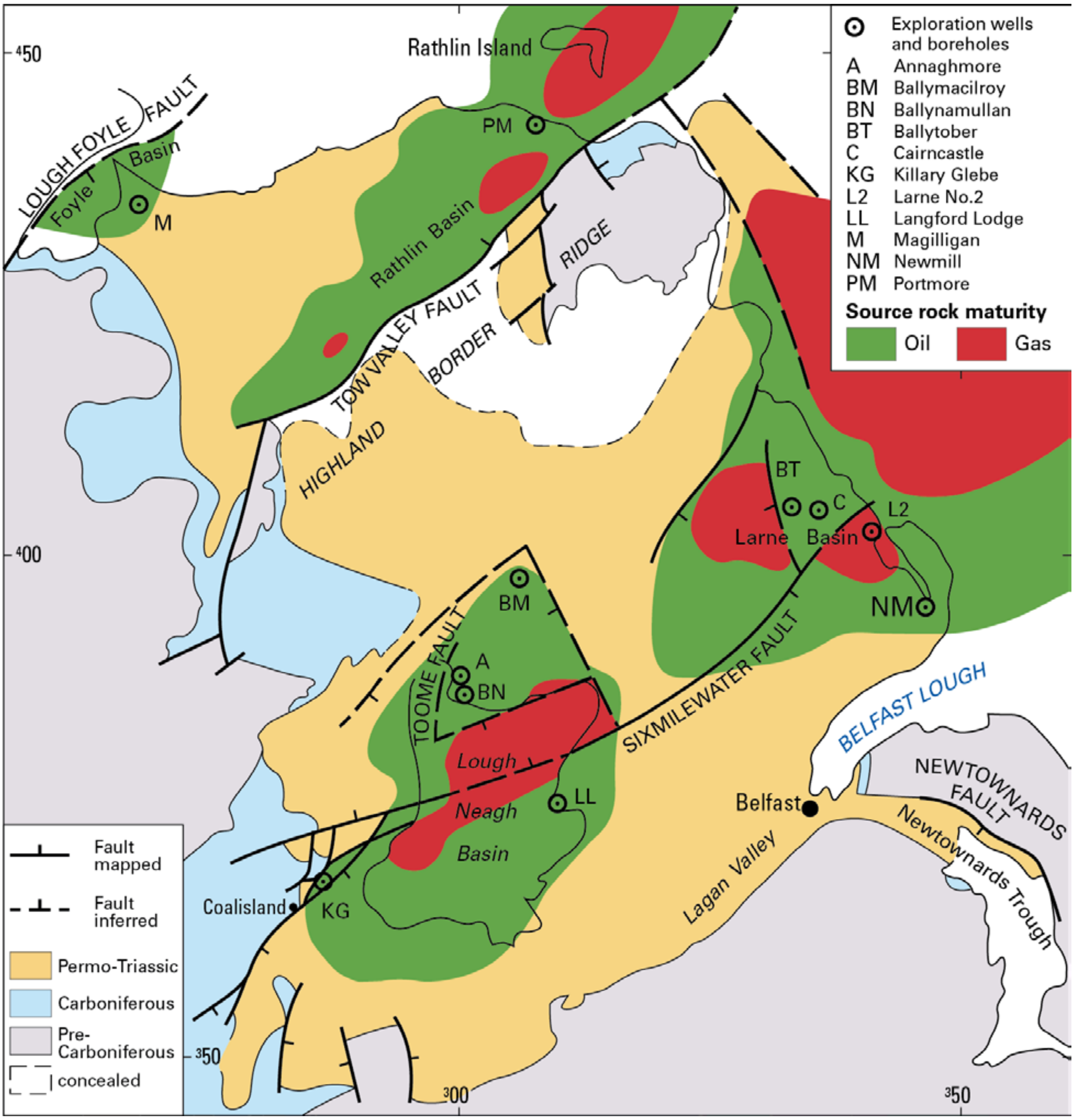


Figure 10 The main basins associated with the Antrim Plateau and their offshore extensions (from Mitchell, 2004). Geological Survey of Northern Ireland,© Crown Copyright.

Several boreholes within the Lough Neagh basin have encountered Lias Group rocks, these include the Ballymacilroy borehole west of Ballymena in the northern part of the basin (Figures 3 and 10), and in the south part, south of Antrim, the Langford Lodge and Mire House boreholes. Of these boreholes only Mire House was found to contain a substantial thickness of Lias Group (approximately 125 m) within the depth range of interest and that might extend southwards for approximately 10 km until cut out by a regional scale fault north of Armagh.

Rock type descriptions

The Waterloo Mudstone Formation (Lias Group) is mainly a calcareous mudstone with subordinate limestone beds, sometimes nodular, that are less than 30 cm thick and variably fossiliferous (Mitchell, 2004). The mudstones tend to be quite soft, whilst the limestone beds are hard due to the presence of calcite cements and fossil shells.

4.2.1.4 MERCIA MUDSTONE GROUP AND PENARTH GROUP: MUDSTONE, SILTSTONE AND SANDSTONE — LSSR

In Northern Ireland, Triassic rocks of the Mercia Mudstone Group and overlying, thinner Penarth Group, are modelled undivided in NGS3D. Both units occur under much of the Antrim Plateau and its margins, located between Limavady and Ballycastle in the north-west and north-east and Armagh and Larne in the south-west and south-east respectively (Figure 3). They tend to be thickest in the main sedimentary basins, that include the Rathlin and Foyle basins in north County Antrim and County Londonderry, and the Larne basin in east County Antrim and Lough Neagh basin in south-west County Antrim and north County Armagh (Figure 9). They thin dramatically onto a broad north-east to south-west orientated ridge of older rocks (known as the Highland Border ridge) positioned between the Tow Valley Fault and Highland Boundary Fault (Figure 9 and Figure 10). The Mercia Mudstone Group and Penarth Group occur mainly within the depth range of interest and is positioned below a thick (up to 1 km) sequence of basalt lava flows known as the Antrim Lava Group (Mitchell, 2004).

Principal information sources

Geological mapping around the margins of the Antrim Plateau has accurately constrained the distribution and thickness of the Mercia Mudstone Group at surface (GSNI, 1997). Below the Antrim Plateau lavas, information on thickness and rock type comes from deep boreholes drilled to explore for hydrocarbons, geothermal energy sources and salt deposits. Within the Larne basin (Figure 9 and Figure 10) a maximum known thickness of about 1000 m of Mercia Mudstone Group is attained in the Larne Borehole (Figure 3 and Figure 11) (Mitchell, 2004). This thickness reduces southwards, due mainly to erosion of the top of the group, such that the thickness in the Newmill Borehole is about 700 m and in the Kilroot Borehole only 230 m is present (Figure 3). In the Lough Neagh basin located under the Antrim Plateau, the thickness of the Mercia Mudstone Group in the Ballymacilroy Borehole west of Ballymena is 492 m, whilst at Langford Lodge south of Antrim only 315 m is present (Figure 3). North of the Tow Valley Fault, which extends from Dungiven to Ballycastle (Figure 3), Mercia Mudstone Group rocks are found within the Rathlin basin (Figure 9 and Figure 10), with 620 m recorded at Port More Borehole near Ballycastle (Figure 3 and Figure 11) and about 400 m proven in the Magilligan Borehole, west of Limavady (Figure 3).

Rock type description

In Northern Ireland six formations can be consistently recognised in the Mercia Mudstone Group and were originally defined in the Port More Borehole (Figure 3 and Figure 11). Overall, the Mercia Mudstone Group consists of calcareous mudstone with thin siltstone beds (Wilson and Manning, 1978). Sandstone is most common in the basal Lagavarra Formation, the transitional unit from the underlying Sherwood Sandstone Group. In higher formations sandstone is largely restricted to beds up to 2.5 m thick called ‘skerries’, for example the Suitcase Sandstone and the Coolmaghra Skerry. They are typically fine-grained, hard and cemented by dolomite (Figure 11).

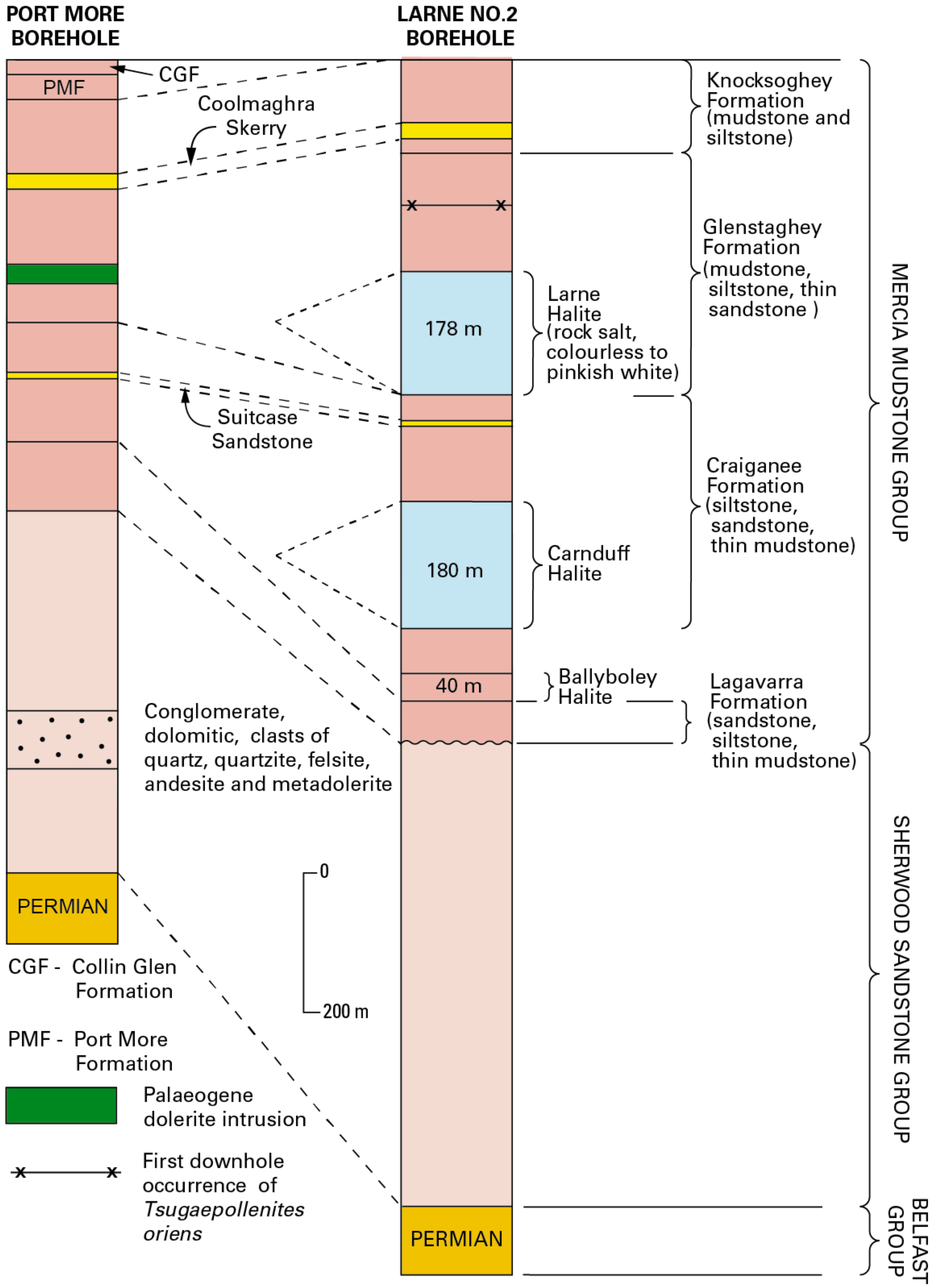


Figure 11 The Permian and Triassic rock sequences recorded by the Port More and Larne No. 2 boreholes. Detail of formations and halite intervals recognised in the Mercia Mudstone Group (Mitchell, 2004). Geological Survey of Northern Ireland,© Crown Copyright.

4.2.1.5 HALITE WITHIN THE MERCIA MUDSTONE GROUP — EVAP

Thick layers of halite (rock-salt) are present under parts of south-east County Antrim between Larne and Belfast (Figure 3). They are known from the Larne and Newmill boreholes in the Larne basin and from the south-eastern margin of the Antrim Plateau on the north side of Belfast Lough, where they are mined for cold weather road treatment.

Principal information sources

In the Larne No. 2 Borehole about 400 m of halite occurs as three separate layers (Figure 11). This halite bearing zone reduces to around 100 m in the Newmill Borehole and only 40 m thick under the north side of Belfast Lough, where it is mined (Mitchell, 2004). In the Larne No. 2 Borehole the three halite layers include the topmost Larne Halite Member, which is 178 m thick and located at the base of the Glenstaghey Formation (Figure 11). The middle and lower halite beds are the Carnduff Halite and Ballyboley Halite members, which are 180 m and 40 m thick respectively, and occur within the Craiganee Formation. In the Newmill Borehole, approximately 9 km to the south-east of Larne No. 2, three halite intervals were also encountered with the Mercia Mudstone Group. The uppermost interval is 25 m thick whilst the middle and lower intervals are 77 m and 86 m thick respectively. The continuity of individual halite layers from borehole to borehole is uncertain; seismic profiles that have attempted to constrain this are inconclusive due to the presence of overlying basalt (Mitchell, 2004).

Rock type description

The Larne, Carnduff and Ballyboley halite member intervals of the Larne No. 2 Borehole (Mitchell, 2004) are dominated by colourless to orange-brown, bedded halite with intermittent bedded gypsum and mudstone partings that also contain abundant halite. The mudstone partings tend to be less than 0.5 m thick but are locally up to 5 m in thickness (Griffiths and Wilson, 1982).

4.2.2 Older sedimentary rock and granites (PRTIs)

4.2.2.1 UNNAMED LATE SILURIAN TO EARLY DEVONIAN IGNEOUS INTRUSION: FELSIC IGNEOUS ROCK — HSR

This unit refers to the Early Devonian age Newry Igneous Complex of Counties Down and Armagh (Figure 12). Its exact shape and vertical extent is not known, but steeply inclined fabrics in each of the three plutons suggest they are steep-sided bodies (Mitchell, 2004). Rock of the Newry Igneous Complex therefore is likely to extend from the surface through the depth range of interest (Figure 12).

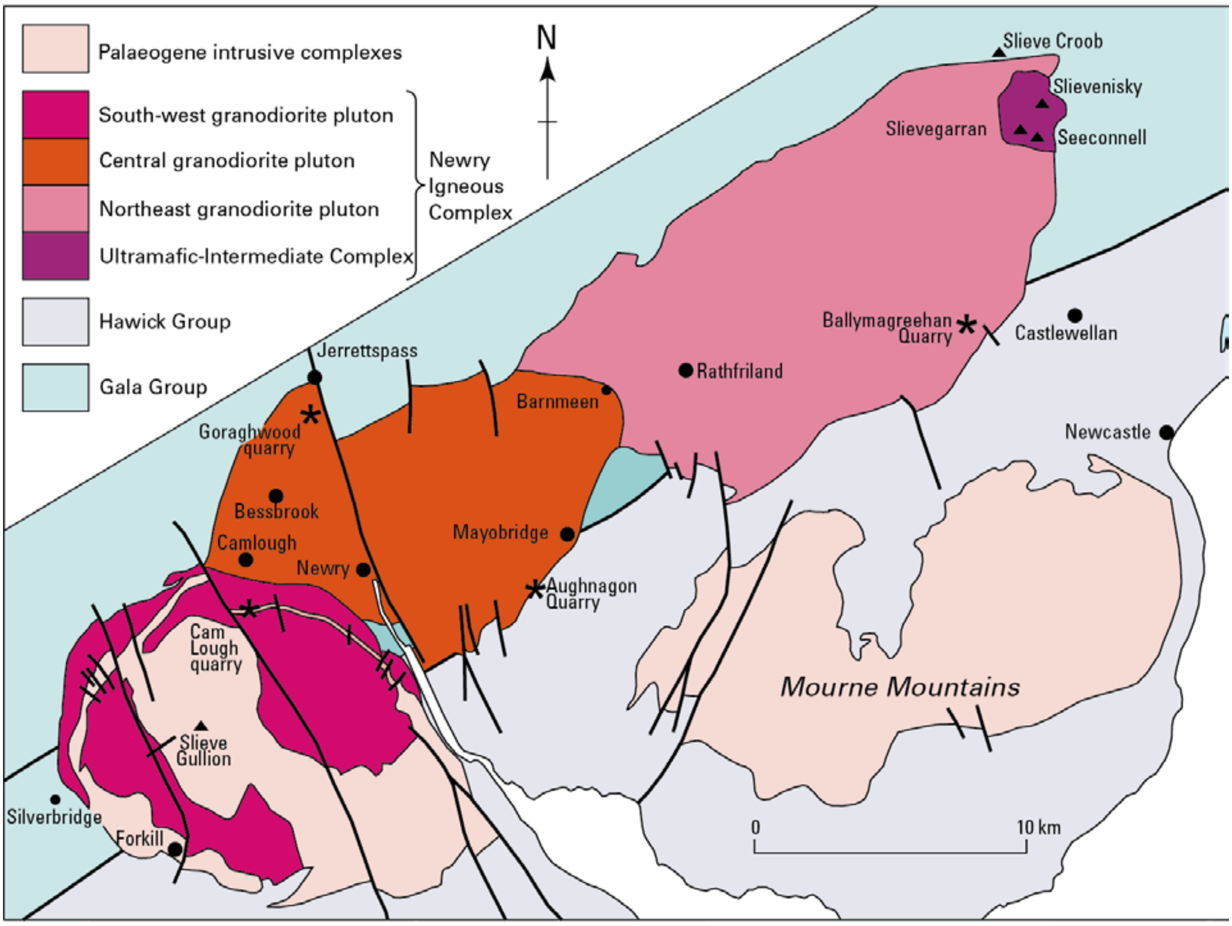


Figure 12 The Newry Igneous Complex HSR and its relationship to the Palaeogene intrusive complexes. (Mitchell, 2004). Geological Survey of Northern Ireland,© Crown Copyright.

Principal information sources

No modern geological survey of the Newry Igneous Complex boundaries exists, however, the extent of the plutons is well constrained by 19th century mapping and Tellus Project geophysics (Young and Donald, 2013).

Rock type descriptions

The Newry Igneous Complex rocks range in composition from granodioritic to granitic from north-east to south-west (Mitchell, 2004). The rocks tend to be medium to very coarse grained and are cut by cooling and other joint surfaces.

4.2.3 Basement rocks

4.2.3.1 Unnamed Ordovician to Silurian igneous intrusion: felsic igneous rock — HSR

This unit refers to the Tyrone Igneous Complex located between Omagh and Cookstown (Figure 3), covering an area of some 350 km^2 (Mitchell, 2004). It is composed of Early Ordovician ocean crust (ophiolite) and volcanic arc-related rocks known respectively as the Tyrone Plutonic and Tyrone Volcanic groups. The Tyrone Plutonic Group occurs mostly to the south of the Tyrone Central Inlier over which it has been thrust (Mitchell, 2004). This section refers to four plutons cut through the Tyrone Igneous Complex and includes the Beragh, Carrickmore, Pomeroy and Slieve Gallion granites (Mitchell, 2004), whose shape and vertical extent is not well constrained but would appear to extend from surface through the depth range of interest (Figure 12). The plutons are elongate parallel to the main Caledonian structural grain which is north-east to south-west and it is possible that some of the plutons join at depth.

Principal information sources

Information on the nature and distribution of the Tyrone Igneous Complex comes primarily from geological mapping (GSNI, 1997). Tellus Project geophysics (Young and Donald, 2013) and research have helped to improve the maps and understanding of the stratigraphy.

Rock type descriptions

The Tyrone Plutonic Group is composed primarily of high strength basic igneous rocks including gabbro and dolerite. The gabbros occur as massive (isotropic) and layered varieties, whilst the dolerite occurs as sheeted dykes. Plutons that cut the Tyrone Igneous Complex rocks are mostly coarse-grained granites but also include fine-grained quartz porphyrys. These rocks have complex networks of cooling and other joints.

4.2.3.2 DALRADIAN SUPERGROUP — HSR

This unit refers to Dalradian Supergroup rocks that occur in the Sperrin Mountains of County Tyrone and County Londonderry, positioned between Londonderry and Omagh to the north and south and Limavady to the east, and in north-east County Antrim between Ballycastle and Cushendall (Figure 3 and Figure 13) (Mitchell, 2004). The rocks have been metamorphosed and deformed to the extent where they are now preserved as schists and pelites. The Dalradian Supergroup is divided, based on rock type, into a number of formations, some of which have HSR characteristics (Table 2). Units included within the NGS3D model that belong to this supergroup include components of the younger Southern Highland Group and older Argyll Group (Table 3).

Principal information sources

Information on the nature and distribution of the Dalradian Supergroup and associated rocks comes primarily from geological mapping (GSNI, 1997). The subsurface extent of formations that comprise the Dalradian Supergroup is not constrained by boreholes.

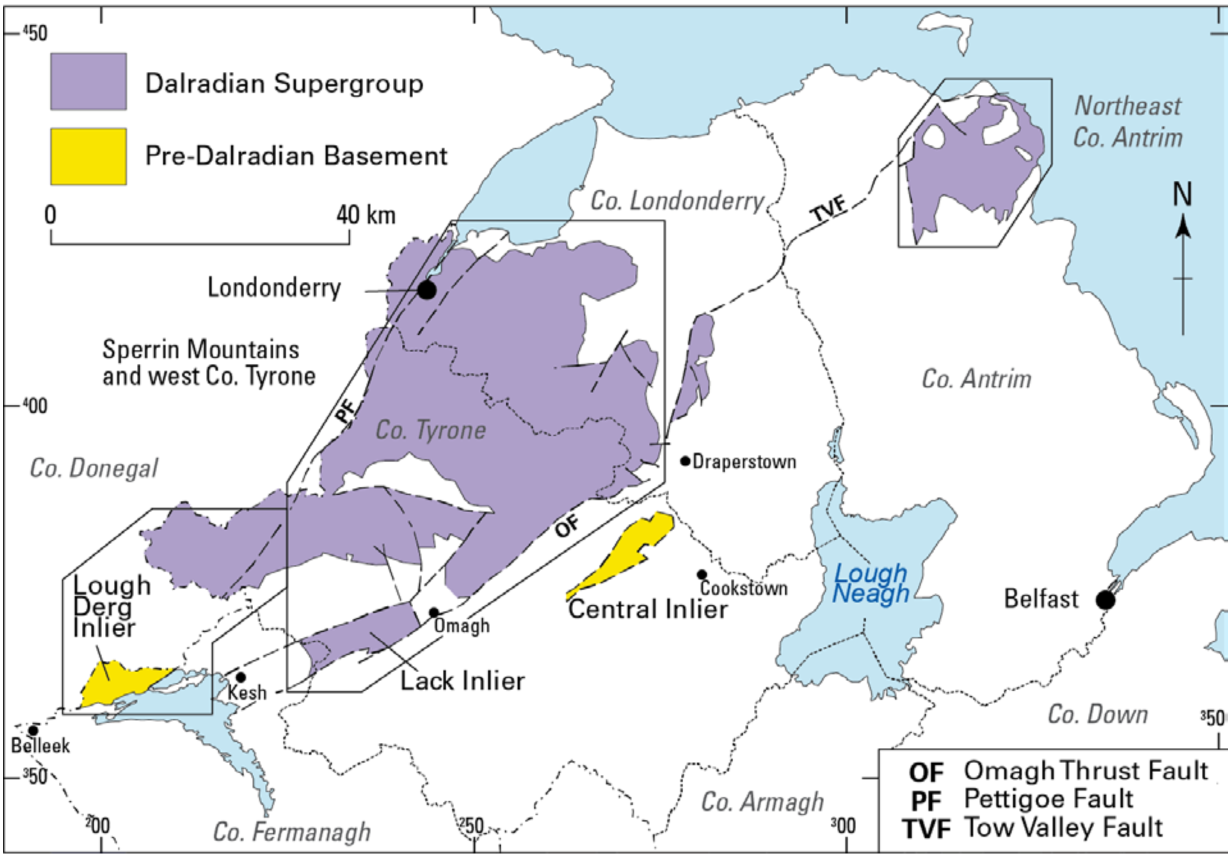


Figure 13 Distribution of Dalradian Supergroup and other pre-Dalradian HSRs in Northern Ireland (Mitchell, 2004). Geological Survey of Northern Ireland,© Crown Copyright.

Rock type description

The Dalradian Supergroup in Northern Ireland has been metamorphosed to greenschist facies and occurs as schistose, sand- and mud-rich rock types known as psammite and pelite respectively. A rock type intermediate to these two is also common and known as semipelite. Less common rock types include basic igneous rocks (basalt, dolerite and gabbro) and limestone intervals. However, most of the Dalradian Supergroup is variably composed of psammite–semipelite-–pelite lithologies that are interbedded on a centimetre to metre scale. These rocks are also variably deformed (folded and thrusted) and dip moderately to the north and north-west. The upper part of the Southern Highland Group consists of a thick succession of turbiditic arenites and pelitic metasediments, with lavas, tuffs and volcaniclastic rocks confined to the lower part of the group. The uppermost unit of the underlying Argyll Group comprises laterally extensive metalimestones with associated psammites, semipelites, pelites, and metavolcaniclastic rocks with and local volcanic pillow lavas. The lower part of the group consists of pale grey, thickly bedded quartzose psammite with pelite interbeds. Within the overall package of Dalradian rocks, basic igneous dolerite and gabbro units occur, referred to as 'unnamed igneous intrusion, Neoproterozoic — mafic igneous rock' in NGS3D. These metabasites were intruded parallel to 'bedding' and as such are sills. Thicknesses vary from sill to sill and can range from a few metres to tens of metres though folding and faulting make the continuity of these hard to predict. Although they have the potential to be considered as PRTIs because of their even igneous texture, they have not been modelled in NGS3D due to their lack of continuity and are therefore not shown on the map.

4.2.3.3 Moine Supergroup — HSR

Two inliers of rock described as pre-Dalradian Supergroup are found south of the main area of the Dalradian Supergroup. They comprise Moine Supergroup gneissose psammites and gneissose semipelites of the Central Inlier in County Tyrone (Figure 13), and psammites of the Lough Derg Inlier in County Fermanagh (Figure 13). These bodies of rock tend to be of lower to upper amphibolite metamorphic grade and are schistose to gneissose in texture (Mitchell, 2004). The rocks of the Moine and Dalradian supergroups are associated with regionally significant faults that impart localised structural complexity.

5 Screening topic 2: rock structure

5.1 OVERVIEW OF APPROACH

This section describes major faults and areas of folding in Northern Ireland and shows their surface extent on a map (Figure 13 and Figure 14). 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: first, they may provide effective limits to any rock volume being considered for siting a GDF; and, second, they may 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 which may impact on the behaviour of groundwater at GDF depths (RWM, 2016b). It was judged that faults with a vertical throw of at least 200 m would be appropriate to the national-scale screening outputs since these would be most likely to have significant fracture networks and/or fault rocks and would have sufficient displacement to juxtapose rock of contrasting physical properties at the GDF scale. However, faults that do not meet the 200 m criterion, but were still considered significant by the regional expert, at the national screening scale of 1:625 000, were mapped and are discussed. It is recognised that many locally important minor faults would not meet this criterion and would be more appropriately mapped during regional or local geological characterisation stages.
Areas of folded rocks are considered to be important in a heterogeneous body of rock, such as interlayered sandstone and mudstone, where the rock mass has complex properties and fold limbs dip at steep angles, potentially resulting in complex pathways for deep groundwater. Where folding occurs in relatively homogeneous rock there is little change in the bulk physical properties and therefore there is less impact on fluid pathways. Hence, areas of folded rocks are defined as those where folding is extensive and/or where folding results in steep to near vertical dips in a heterogeneous rock mass of strongly contrasting physical properties at a national screening scale of 1:625 000 (RWM, 2016b). Their locations are indicated on the map in general terms and the nature of the folding is discussed.

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

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

5.2 REGIONAL TECTONIC SETTING

The surface and subsurface structure of Northern Ireland can be described in terms of three major mountain building events (orogenic cycles) that affected the region and surrounding areas: the Caledonian, Variscan and Alpine orogenies (Pharaoh and Haslam, 2018). The Caledonian Orogeny includes two cycles of deformation and faulting known as the Grampian event, which occurred during the Early to Mid Ordovician (Mitchell, 2004), and the late Caledonian event which took place during the late Silurian to Early Devonian (Cooper et al., 2013). The Variscan Orogeny occurred from the mid to late Carboniferous (Mitchell, 2004). The Alpine Orogeny continues, and has affected the region since the late Mesozoic (e.g. Cooper et al., 2012. In this account, 'basement' rocks are older than Devonian, whilst the use of term 'cover' relates to Devonian and younger rocks.

The Northern Ireland region is underlain by three distinct areas of basement rocks known as terranes (Anderson et al., 2004). From north-west to south-east these are: the Grampian terrane which is bound to the south-east by a westward continuation of the Highland Boundary Fault of Scotland; the Midland Valley terrane which is bound to the north by the Highland Boundary Fault and to the south by the Southern Upland Fault (Figure 3). South-east of the Southern Upland Fault is the Southern Upland–Down–Longford terrane, bound to the south in the Republic of Ireland by the Navan Fault, which is thought to represent a surface expression of the Iapetus suture zone.

The Grampian terrane is composed of moderately metamorphosed, mainly sedimentary rocks (Dalradian Supergroup) that occur at surface in the Sperrin Mountains and the north-east Antrim Inlier. They are the oldest rocks in Northern Ireland and record all three orogenic events.

Within the Midland Valley terrane an accreted micro-continental block and slithers of volcanic arc and ophiolite are exposed between Omagh and Cookstown and are known as the Tyrone Central Inlier and Tyrone Igneous Complex (Mitchell, 2004). The Tyrone Central Inlier is understood to be a higher metamorphic grade, equivalent of the Dalradian Supergroup (Cooper et al., 2011), whilst the Tyrone Igneous Complex is younger (Early to Mid Ordovician).

Following closure of the Iapetus Ocean and the ensuing Caledonian Orogeny, extension and subsidence resulted in the formation of the basins across much of Northern Ireland from the late Silurian to mid Carboniferous (Mitchell, 2004). Reactivation of Grampian and late Caledonian faults played a key role in the positioning and extent of subsequent basins of the Southern Upland–Down–Longford terrane and the deposition of Ordovician to Silurian sedimentary rocks across counties Armagh and Down (Anderson, 2004). Devonian sediments of the Midland Valley terrane were deposited in fault-controlled basins associated with late Caledonian regional-–scale, sinistral, strike-slip faulting and uplift (Mitchell, 2004).

Early Carboniferous extensional faults were again reactivated during the late Carboniferous Variscan Orogeny, and were subjected to variable stresses that led to the formation of dextral strike-slip faults and thrusts and the development of small coal-bearing basins, for example near Ballycastle in north County Antrim and between Dungannon and Coalisland in east County Tyrone.

From the late Permian, Northern Ireland experienced extensional tectonics that resulted in the reactivation of older east-north-east to west-south-west-faults, and development of north-west and north-north-west-trending normal faults, that bound basins belonging to the 'Clyde Belt' which extends offshore through the Irish Sea (Mitchell, 2004). Onshore in Northern Ireland these basins are mostly concealed by younger rocks and include the Foyle basin, which is bound by the regionally important north-east trending Pettigoe Fault–Foyle Fault, and the Rathlin basin bound by the north-north-west-trending Tow Valley Fault.

Palaeogene tectonics and magmatism, related to opening of the North Atlantic Ocean and the Alpine Orogeny (Cooper et al., 2012), have affected all of Northern Ireland (Mitchell, 2004). Two main phases of faulting and basin formation are known to have occurred during the Paleocene–Eocene and Eocene–Miocene (Mitchell, 2004). The earlier event was extensional and caused reactivation of older, north-west and north-north-west-trending faults. The later phase of tectonism was compressional and led to the formation of strike-slip basins, such as Lough Neagh (Mitchell, 2004) located at the south-west corner of the Antrim Plateau. Regionally important structures including the Camlough, Newry, Portrush and Loughguile dextral strike-slip faults, trending north to north-north-west, appear to have acted in conjunction with east-north-east-trending sinistral faults, such as the Tow Valley, Tempo–Sixmilecross–Carnlough, Clogher Valley–Sixmilewater, and Kinnegoe faults at this time (Cooper et al., 2012).

5.3 MAJOR FAULTS

The major faults selected from analysis of the UK3D model in the Northern Ireland region (Figure 14), exhibit a variety of orientations and evolutionary histories, as described above. The following sections describe major faults within each of the three basement 'domains' (terranes) which are the Grampian, Midland Valley and Southern Uplands–Down–Longford terranes (Figure 14).

5.3.1 Grampian terrane

The Grampian terrane is positioned north of the east-north-east trending Belhavel and Omagh thrust faults located either side of Omagh in the west of Northern Ireland, whilst, to the east of Draperstown a continuation of these faults is believed to be the concealed Highland Boundary Fault which is located beneath cover rocks as far as Cushendall. During the initial Grampian event, regional metamorphism and deformation took place in response to the earliest stages of closure of the Iapetus Ocean, and are thought to have been driven by the collision of a micro-continental block and slithers of volcanic arc and ocean crust (ophiolite) that were added (accreted) on to the continental margin in this region (Cooper et al., 2011; Hollis et al., 2012). This initial orogenic event led to the formation of east-north-east-trending folds and thrust faults throughout the Dalradian Supergroup.

The late Caledonian event caused little deformation in the Grampian terrane, but was associated with large igneous intrusions across the border in Ireland and in the Sperrin Mountains near Strabane, where a suite of trachyandesitic minor intrusions are observed to have taken advantage of Grampian event thrust faults within the Dalradian Supergroup (Cooper et al., 2013).

The Grampian terrane comprises numerous named and unnamed fault strands. Those identified in UK3D include the east-north-east-trending Belhavel Fault; the Omagh Thrust Fault; the Pettigoe and Tow Valley faults; the east-trending Cool Fault; and the north-south-trending Portrush and Loughguile faults.

The Omagh Thrust Fault was particularly significant during the Grampian event as it facilitated the south-east-directed transport of older Dalradian Supergroup rocks over the younger Tyrone Igneous Complex by an unknown distance, but most likely several kilometres (Cooper et. al., 2011). The Omagh Thrust Fault is believed to continue to the east, concealed beneath the Antrim Plateau, as the Highland Boundary Fault. The Omagh Thrust and Highland Boundary Fault can be traced over a distance of 42 and 66 km respectively. Both faults dip at low to moderate angles to the north and have a reverse sense of throw of unknown distance.

The Belhavel Fault has an east-north-east trend and a length in excess of 54 km. The fault dips gently to the north with a reverse sense of throw of unknown distance.

Both the Belhavel Fault and Omagh Thrust Fault are considered to be key Grampian event structures that have subsequently been reactivated during Variscan and Alpine orogenic events. Extension during the early Carboniferous was mostly focused on the Belhavel and Omagh thrust faults west of Omagh, and on the Tow Valley Fault on the Antrim Plateau (Mitchell, 2004).

The Tow Valley Fault trends east-north-east to west-south-west swinging to more north-north-east to south-south-west westwards to merge with the Omagh Thrust. The Tow Valley Fault forms the northern boundary to the concealed Highland Border ridge and has a length in excess of 93 km. The fault dips steeply to the north with a normal throw of around 850 m as shown in UK3D. Repeated phases of extension and sediment deposition north of the Tow Valley Fault, from the Carboniferous to Oligocene, have resulted in the juxtaposition and (syndepositional) thickening of cover rocks against the basement rocks of the north-east County Antrim Inlier and Highland Border ridge, which appears to have remained a relative basement high throughout this time period.

Variscan orogenic thrusting reactivated and steepened the Omagh Thrust Fault and transported the Dalradian Supergroup over both Devonian and Carboniferous rocks again by an unknown but considerable distance (Mitchell, 2004). The following phase of Variscan tectonics saw dextral strike-slip movement on the east-north-east-trending Belhavel and Omagh thrust faults and the parallel Cool Fault west of Omagh, which resulted in the formation of the Lack Inlier. The Cool Fault is an east-trending fault dipping and throwing to the north. UK3D estimates a normal throw of more than 1000 m over the fault zone and defines the southern margin of a Carboniferous basin.

Permian and Triassic age extension took place on the north-east-trending Pettigoe–Foyle Fault in the Foyle basin near Londonderry, whilst further east towards Ballycastle, the north-north-west-oriented Tow Valley Fault was the main structure that allowed thick packages of sedimentary rocks of Permian and Triassic age to be deposited in the Foyle and Rathlin basins. The Pettigoe–Foyle Fault in the north-west of the region has a length in excess of 174 km and dips steeply to the south-east with normal throw to the south-east of unknown distance.

Tellus project airborne magnetic data (Young and Donald, 2013) have revealed approximately 0.65 km of sinistral strike-slip displacement across the Omagh Thrust Fault after formation of the Palaeogene Antrim Lava Group (Cooper et al., 2011). Eocene–Miocene extension on the Tow Valley, Portrush, Carnlough, Sixmilewater and Kinnegoe faults resulted in basin development and deposition of the Lough Neagh Group in parts of County Antrim (Mitchell, 2004). The Portrush and Loughguile faults both dip steeply to the west and throw to the west with a normal throw in excess of 600 m. The faults are at least 60 km and 45 km in length respectively.

5.3.2 Midland Valley terrane

The Midland Valley terrane comprises numerous named and unnamed fault strands. Those identified in UK3D include the east-north-east to west-south-west-trending Tempo–Sixmilecross Fault; Carnlough Fault; Sixmilewater Fault; Clougher Valley Fault; Davagh and Beleevnamore faults, east–west-trending Killadeas–Seskinore Fault; and the north–south-trending Ballyober Fault.

The Midland Valley terrane is bound to the north by east-north-east to west-south-west-oriented Belhavel and Omagh thrust faults (discussed in the Grampian terrane section) and the concealed Highland Boundary Fault. Its southern limit is believed to be controlled by the mostly concealed Southern Upland Fault.

Major structures within the area of the Tyrone Igneous Complex include the north-east to south-west Davagh and Beleevnamore faults, which are believed to have been Grampian event thrusts that transported the Tyrone Igneous Complex northwards over the Tyrone Central Inlier by many kilometres (Cooper et al., 2011; Hollis et al., 2013) and resulted in the juxtaposition of rock units of the Dalradian Supergroup, Tyrone Igneous Complex and Tyrone Central Inlier. Folding within the Tyrone Igneous Complex is present but is not well understood.

From Early to Late Devonian times, sinistral strike-slip faulting and extension, related to the late Caledonian event, caused basin formation in the Midland Valley terrane in an area referred to as the Fintona block. The Fintona block is bound to the north by the Omagh Thrust Fault and includes the reactivated Kildeas–Seskinore, Tempo–Sixmilecross and the Clogher Valley faults.

Subsequent Variscan orogenic reactivation resulted in dextral strike-slip movement of the Kildeas–Seskinore, Tempo–Sixmilecross, Clogher Valley, Elagh and Sixmilewater faults. Dextral movement on the Clogher Valley Fault and the Elagh Fault produced a structurally complicated area between Coalisland and Clogher. There is gentle folding of both Devonian and Carboniferous rock units within this area, but the main complication is the faulting. The Elagh Fault, the northern branch of the Sixmilewater Fault, has a length of approximately 53 km and forms the northern boundary of the complex pull-apart basin to the south between the Elagh–Clogher Valley Fault and the Sixmilewater Fault. It is uncertain how these faults connect as the confluence is concealed beneath Lough Neagh. The Sixmilewater Fault has a length of 67 km and a normal throw greater than 1 km to the south (UK3D). The Clogher Valley Fault to the west has a mapped length of at least 82 km long, dipping to the south with a throw to the south of approximately 1 km (as shown in UK3D). Permian and Triassic age extension was responsible for development of the Lough Neagh and Larne basins whose size and shape are controlled by north-north-west-oriented faults including the Sixmilewater Fault and the concealed extension of the Highland Boundary fault zone (Mitchell, 2004).

The Tempo–Sixmilecross Fault extends through the northern half of the terrane with a mapped length greater than 73 km, dipping and throwing to the south by 1.5 km (as shown in UK3D). Strike-slip movement on the Tempo–Sixmilecross Fault resulted in formation of the smaller Lisbellaw Inlier. The Variscan Orogeny caused some gentle folding of Devonian and Carboniferous strata in proximity to pop-up structures. The Killadeas–Seskinore Fault splays from the Tempo–Sixmilecross Fault in the west and has a mapped length greater than 33 km, dipping and throwing to the south by 1.5 km (UK3D). The Carnlough Fault in the east of the Midland Valley terrane has a mapped length greater than 21 km, dipping and throwing to the south by an unknown distance (UK3D). The Carnlough Fault may link with the Toome and Sixmilewater faults westwards.

Within the Lough Neagh and Larne basins north-west and north-north-west-orientated faults are known to be important in controlling localised deposition of Mesozoic and possibly Cenozoic rock strata for example the

Ballytober Fault west of Larne (Waters et al., 2015). The Ballytober Fault is a modelled in UK3D as a steep, west-dipping structure with a throw of about 1430 m and a mapped length of at least 11 km.

The regional airborne magnetic survey of the Tellus Project (Young and Donald, 2013) has revealed approximately 2.3 km of sinistral strike-slip displacement of Palaeogene-age dyke swarms that cross the Tempo–Sixmilecross Fault (Cooper et al., 2011).

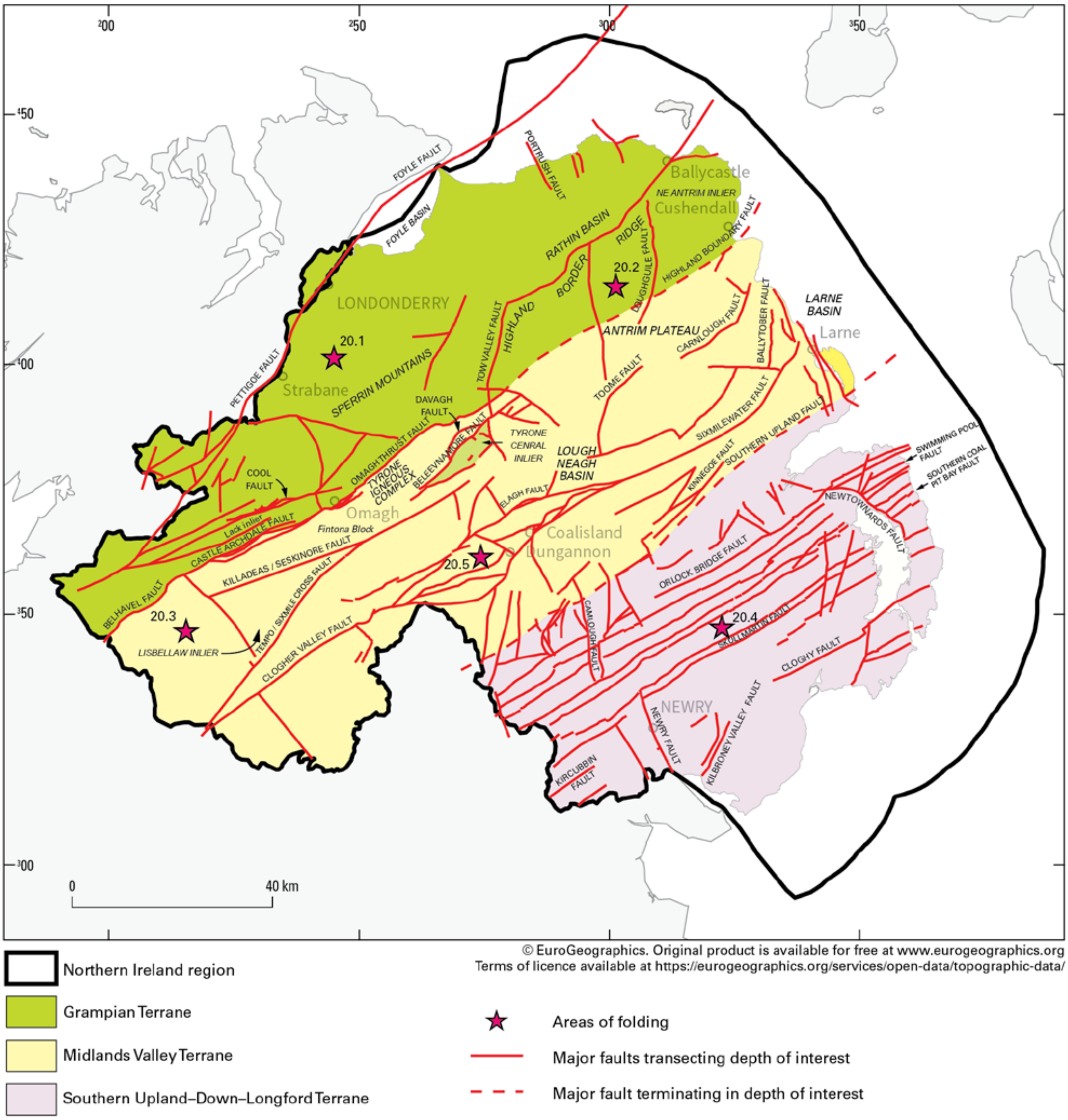


Figure 14 Major faults and areas of folding in Northern Ireland. Contains EuroGeographics data ©EuroGeographics. Contains British Geological Survey digital data © UKRI 2018

5.3.3 Southern Uplands–Down–Longford terrane

The Southern Upland–Down–Longford terrane is an accretionary prism composed of east-north-east to west-south-west-oriented slivers of tightly folded Ordovician and Silurian sedimentary rocks, known as tracts, which are bound by steep thrust faults including the Southern Uplands, Orlock Bridge and Cloghy faults. The Southern Upland fault is a concealed, south-south-east-dipping northern-bounding fault of the Southern Uplands–Down–Longford terrane and is interpreted to extend westwards into the Republic of Ireland and eastwards across the Irish Sea into Scotland. The fault is mapped with a length of over 100 km. The Orlock Bridge, Cloghy, Kircubbin, Skullmartin, Southern Coalpit Bay, and Swimming Pool faults are parallel to and southwards of the Southern Upland Fault. All are steep strike-slip faults with mapped lengths in excess of 90 km with unknown throw. Additionally there are a number of unnamed high-angle faults/tracts which transect southern Northern Ireland and the Southern Uplands–Down–Longford terrane parallel to the faults named above.

The final closure of the Iapetus Ocean is believed to have driven the late Caledonian event and was responsible for regional-scale magmatism and uplift. Within the Southern Upland–Down–Longford terrane the late Caledonian, Newry Igneous Complex comprises three steep-sided plutons oriented parallel to tract boundary faults including the Cloghy Fault. These plutons appear to have been emplaced between the tract boundaries in response to regional sinistral strike-slip faulting which was operating at the time of magma production (Cooper et al., 2016).

Permian and Triassic age extension led to the formation of the Newtownards Trough, which is a half-graben basin bound to the east by the north-west to south-east-orientated Newtownards Fault with a mapped length of approximately 23 km, dipping and throwing to the west juxtaposing Triassic sediments against Silurian rocks (Mitchell, 2004).

Fault movements related to the Alpine Orogeny have been inferred from the high-resolution Tellus project magnetic data (Young and Donald, 2013), with approximately 2.4 km of dextral strike-slip displacement across the late Caledonian Newry Igneous Complex and Palaeogene intrusions associated with the Camlough and Newry faults in the vicinity of Slieve Gullion near Newry (Cooper et al., 2011). These fault movements are believed to be contemporaneous with sinistral strike-slip movement on the Tempo–Sixmilecross Fault as described above in the Midland Valley terrane.

5.4 FOLDING

Areas where folding is considered to be a notable feature in the region are highlighted in Figure 14. These areas, potentially comprising multiple structures, are described below in addition to named fold structures that occur in other parts of the region.

The degree and magnitude of folding within the region largely reflects the orogenic events that have affected the rocks. As with the major faults, folding can be described in terms of the terranes and the age of the rocks. The rocks can be described in terms of basement rocks (older than Devonian), and cover rocks which are Devonian and younger.

The basement of the Grampian terrane consists of greenschist to granulite facies metamorphic rocks with complex north, south-east, west and east–west-orientated folds, whose axes are moderately to steeply inclined to the north and north-west (Figure 14; location 20.1). The Highland Border ridge, which is bound to the north by the Tow Valley Fault and the south by the Omagh Thrust Fault, possibly brings a region of Grampian Folding (beneath cover sequences) into the depth range of interest (Figure 14; location 20.2). In the Midland Valley terrane the basement is uncertain because of the extensive cover. North of the Tempo–Sixmilewater Fault and Cool Fault, Grampian terrane-type folding is expected in the basement rocks (Figure 14; location 20.3). To the south of the Tempo–Sixmilewater and Cool faults, Ordovician and Silurian rocks are more gently folded. The basement of the Southern Upland–Down–Longford terrane is tightly folded and steeply inclined between the fault tracts that cross the terrane (Figure 14; location 20.4).

The Devonian and Carboniferous sequences are faulted and gently folded by Variscan tectonics, especially dextral transpression, which has resulted in some zones of more intense deformation adjacent to major structures such as the Omagh Thrust and between the Clogher Valley, Elagh and Sixmilewater faults (Figure 14; location 20.5). There is no significant folding within the cover sequences except where associated with faulting.

5.5 UNCERTAINTY

A fault is recognised as being present because distinctive units of strata are offset by varying amounts relative to one another, both horizontally and vertically. If the fault dip is known then the sense of throw (normal or reverse) can also be determined. Surface evidence is based on geological mapping, where faults may be seen at crop, or their presence, attitude and location may be ascertained from mapping offset formational boundaries, for which the degree of confidence is in turn dependent upon the nature and degree of confidence in mapping those adjacent formations at crop. It is important to understand the nature of geological faults, and the uncertainties which attend their mapped position at the surface. Faults are planes of movement along which adjacent blocks of rock strata have moved relative to each other. They commonly consist of zones, perhaps up to several tens of metres wide, containing several to many fractures. The portrayal of such faults as a single line on the geological map is therefore a generalisation.

The presence, subsurface location, attitude and displacement of faults, may be evidenced by geophysical techniques. These techniques themselves carry varying degrees of confidence, depending on their varying degrees of sensitivity and thus resolution. Potential field (gravity and aeromagnetic) data are the least sensitive techniques on which to base interpretations, with structures identified and mapped tending to be larger scale. Northern Ireland has benefited from the Tellus project (Young and Donald, 2013) which included region-wide, high-resolution airborne geophysics. Both magnetic and electromagnetic images have proven particularly useful in helping to identify faults, unconformities and magnetic/non-magnetic rock packages and bodies. Seismic reflection data, acquired during hydrocarbon exploration in Northern Ireland, can provide greater resolution and thus permit more accurate identification, location and mapping of fault(s) and other structures in the subsurface. The quality of seismic data varies with the age of its acquisition and the nature of the underlying geology. Seismic data acquired for the area of the Antrim Plateau, particularly where there is basalt at surface is generally not good, and is of limited value.

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 Northern Ireland region, 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. It includes 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 greater than 15º C) which 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 NORTHERN IRELAND

Across the region there is very limited information in relation to groundwater, either in terms of groundwater movement or chemical composition, in the depth range of interest (200 to 1000 m). Almost all the information is related to the relatively shallow groundwater systems which are currently exploited only in a 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

Northern Ireland has a diverse and complex geology and this is reflected in the hydrogeology of the region. Compared with some other regions in the United Kingdom, Northern Ireland is underlain by rocks that have a generally poor capacity for groundwater flow and the use of groundwater for public supply is limited. Groundwater has been estimated to contribute only about six per cent of public water supply in Northern

Ireland (Mitchell, 2004). Where groundwater is present it is generally obtained from formations with limited surface expression.

The regional groundwater systems in Northern Ireland are controlled by the broad distribution of geological units (Table 3) and the regional geological structure; the hydrogeological characteristics of those units; and topography and the distribution of till and soils, and hence the distribution of recharge. The overall hydrostratigraphy of the region is conceptualised in terms of the four broad geological divisions across Northern Ireland:

- ***groundwater system within the younger sedimentary and igneous cover rocks*** – primarily associated with the Antrim Plateau, including Permian to Cretaceous sediments and Palaeogene volcanic rocks
- ***groundwater system consisting of older cover rocks*** – includes varied igneous and sedimentary deposits of Devonian and Carboniferous age, primarily between Omagh in the north, Enniskillen in the west and Dungannon and Armagh in the east
- ***groundwater system composed of Ordovician and Silurian sedimentary basement rocks*** – in the south-east of the region between Armagh and Belfast to the north-west and north-east and Newry and Downpatrick to the south-west and south-east
- ***groundwater system associated with the Precambrian metamorphic and Ordovician igneous basement rocks*** – between Londonderry and Omagh, primarily underlying the Sperrin Mountains in the north-west of the region

Of these four groundwater systems, only two, the young cover rock sequence in the north-east and the older cover rock sequence in the south-west, have been designated as showing significant potential for groundwater resources (Mitchell, 2004), with the most favourable hydraulic properties for groundwater supply found in the Quaternary deposits and the Sherwood Sandstone Group (Mitchell, 2004).

Note that the groundwater systems are not entirely restricted to specific sub-regions in Northern Ireland. For example, some Carboniferous sedimentary rocks that are part of the Devonian and Carboniferous groundwater system in the south-western part of the region, are also found as outliers within the Precambrian and Ordovician groundwater system of the north and north-west of the region.

Rocks from all four of the groundwater systems are found in the depth interval of interest across the region. Potential pathways for groundwater movement between units are described after each of the groundwater systems is discussed in turn in the following sections.

6.3.1 Hydrogeology of the Palaeogene volcanic and Cretaceous to Permian sedimentary cover rocks

The younger Palaeogene volcanic and sedimentary cover rocks are primarily exposed across the Antrim Plateau which dominates over 30 per cent of the province. Within the sub-region four basins underlie the plateau, the Foyle, Rathlin, Lough Neagh and Larne basins.

There is limited information regarding the hydrogeology of the younger sedimentary cover (Cretaceous to Permian sediments) and Palaeogene igneous rocks of the depth interval of interest in the references reviewed. This groundwater system contains a number of principal aquifers (Ulster White Limestone Formation and Hibernian Greensand Formation; Sherwood Sandstone Group, and the Permian Enler Group) that are locally developed for groundwater and there is some information on the hydrogeological characteristics of these units from the zone of active exploitation. This is summarised below along with information on intervening units such as the Lias Group and Mercia Mudstone Group that can locally act to confine the sequence and on Palaeogene igneous rocks in the Antrim Plateau.

6.3.1.1 PALAEOGENE IGNEOUS ROCKS

Palaeogene granitic intrusions within the Southern Uplands–Down–Longford terrane, consist of the Slieve Gullion ring complex, Mourne Mountains Complex and Carlingford Complex (in the Republic of Ireland). The high relief associated with these units promotes shallow groundwater flow via secondary fractures along short flow paths (Robins, 1996). Water has been encountered in rare joints in the granite of the Mourne Mountains Complex, such as in the Slieve Binnian tunnel (Manning, 1971). Shallow groundwater in the Mourne Mountains Complex is calcium carbonate trending towards calcium sulphate type, and tends to generally be acidic, due mainly to the upland terrain (Robins, 1996).

Numerous dykes of Palaeogene age are found across much of the region. There is evidence that although the Palaeogene dykes generally act as a barrier to groundwater flow (e.g. local compartmentalisation of the Sherwood Sandstone aquifer), secondary porosity, fractures and joints permit transport of water laterally along the dykes, with saline water being encountered in the Kilroot Salt Mine, near Carrickfergus in Mercia Mudstone Group rocks (Manning, 1971).

Sills may be important pathways for water through successions of mudrock and a Palaeogene sill, the Port More sill, is present at the depth of interest in the Antrim Plateau. However, there is no hydrogeological information on it available in the sources consulted.

6.3.1.2 CRETACEOUS SEDIMENTARY AND PALAEOGENE VOLCANIC ROCKS

The Ulster White Limestone Formation, a Cretaceous compacted chalk, and the Hibernian Greensand Formation underlie about a quarter of the Northern Ireland region. Groundwater flow through them occurs via relatively shallow, complex karst and fracture systems in the limestones and as intergranular flow within the sandstones of the Hibernian Greensand Formation. The majority of these rocks overlie older Permian, Triassic and Jurassic sedimentary rocks and are confined by younger Palaeogene basalts, with small strips of outcrop found around the edges of the Antrim Plateau, where the Ulster White Limestone and Hibernian Greensand formations crop out, (McConvey, 2005). In these units, favourable conditions for exploiting groundwater have been encountered (Robins, 1996) and the two formations act as a single aquifer unit (Robins, 1996).

The Ulster White Limestone Formation comprises harder and much less porous rock than its English Chalk counterpart. The majority of recharge to the unit is at outcrop, but there is some infiltration from the overlying basalt lavas into concealed chalk. There is some evidence that flow decreases with depth as the secondary porosity decreases with increasing overburden thickness beneath the basalt: a 274 m deep borehole at Corbally Reservoir, near Portrush encountered chalk at depth below basalt, but no water was obtained. Karst features are present, with sinks common where rivers and streams flow off the basalt onto chalk (Robins, 1996). Cretaceous, mainly chalk, groundwaters at outcrop are typically of calcium bicarbonate type. The chemistry of the confined chalk groundwater is unknown. However, the groundwater in the chalk below 361 m of basalt at Aughrimderg is artesian and ^{14}C data indicates an age of 13 000 years (Barnes et al., 2003).

Across the Lough Neagh basin, the Cretaceous rocks are overlain by the Palaeogene Antrim Lava Group. Here there is evidence of some hydraulic connection with the underlying Ulster White Limestone. Groundwater conditions are variable in the basalt (Robins, 1996) and groundwater flow is through secondary fracture porosity (Robins, 1996). The lack of sizeable springs from the base of the basalts where they crop out around the edge of the plateau has been inferred to mean that surplus groundwater flows down to recharge the underlying chalk (Robins, 1996). Faulting during the Palaeogene resulted in fault-bounded blocks of lavas forming basins into which Oligocene sediments were deposited to form the Lough Neagh Group. These are predominantly made of up to 380 m of clays, thin lignite beds and conglomerates. These sediments have very low relative permeabilities (McConvey, 2005) and the Lough Neagh Group therefore confines both the basalts and underlying Cretaceous rocks.

6.3.1.3 JURASSIC TO PERMIAN SEDIMENTARY ROCKS

Permian and Triassic sedimentary rocks are present across the Antrim Plateau. The majority of these rocks are concealed by younger, mostly Cretaceous and Palaeogene rocks, with small areas of outcrop found around the edges of the Antrim Plateau. The Sherwood Sandstone Group and Enler Group are considered regionally important formations for groundwater (McConvey, 2005) and have been historically targeted for potable water supplies. The Connswater Marl Formation, Mercia Mudstone Group, Penarth Group and Waterloo Mudstone Formation (Lias Group) are low-permeability strata that confine water in the underlying Enler and Sherwood Sandstone groups. There is only limited hydrogeological information available on these low-permeability strata in the information sources consulted for the depth interval of interest.

The Sherwood Sandstone Group crops out in four areas; the Lagan and Enler valleys between Moira and Newtownards, including Belfast; south of Dungannon; Cookstown and the Roe valley between Limavady and Dungiven. The properties of the sandstone vary spatially. For example, the area between Newtownards and Comber has relatively high permeability (Robins, 1996). Laboratory measurements of cores from depths of up to 555 m from the Sherwood Sandstone Group aquifer near Dungannon and Cookstown indicated intergranular permeability an order of magnitude less than those observed at Englishtown near Lisburn (Robins, 1996).

However, the aquifer properties of the sandstone at Bolea, in the Roe valley below 24 m of Mercia Mudstone Group appear comparable to those in the Lagan valley (Robins, 1996).

The Sherwood Sandstone Group dips towards the centre of the basins underlying the Antrim Plateau. It is affected by faulting, and is typically found at depths greater than 1000 m below the ground surface across most of the Antrim Plateau where it is confined by mudstones of the Waterloo Mudstone Formation and Mercia Mudstone Group. During drill stem tests on two sections (1396–1412 m and 1347–1357 m) of Sherwood Sandstone in the Larne No. 2 Borehole, where the top of the formation is 968 m below the surface, the piezometric surface was measured at 13 m and 10 m, respectively below ground level indicating confined conditions (Downing et al., 1982). Dykes are known to act as barriers to groundwater flow through the country rock into which they have intruded, compartmentalising groundwater flow (e.g. in the Sherwood Sandstone Group, Manning, 1971). However, segmentation both vertically and horizontally means that dykes are not continuous sheets and as such groundwater is able to move through transfer zones, so the dykes act more as baffles than barriers.

Shallow groundwaters from Permian and Triassic rocks at outcrop are typically of the calcium magnesium bicarbonate type (Robins, 1996). However, hydrochemistry and temperature measurements from samples at or below the depth range of interest attest to the variability in chemical composition and age of groundwater in this depth interval. Geochemical investigations using isotopes in the Lagan valley indicated the existence of compartments of the Sherwood Sandstone Group aquifer that contained 3000–4000-year-old groundwater, in contrast to the majority of Northern Ireland’s groundwater that is relatively young and subject to active recharge (Mitchell, 2004). Measurements of tritium concentration in the sandstone at Bolea indicated little active recharge was taking place (Robins, 1996). Mineralisation measurements of water samples from the Triassic Sherwood Sandstone Group, obtained from drill stem tests in boreholes drilled in the Lough Neagh basin (Ballymacilroy) and the Larne basin (Larne No. 2) at depths of 1534 and 1347 m below ground level, respectively, show values roughly four to six times the salinity of sea water (Robins, 1996; Downing and Gray, 1986). The oxygen and hydrogen stable isotope ratios were similar to shallow groundwaters, indicating that these fluids are of meteoric rather than connate origin and have not undergone significant isotopic exchange with the aquifer material. Instead, they have been flushed through the aquifer system by natural flow, which according to temperature evidence is still taking place (Downing and Gray, 1986). The Sherwood Sandstone Group was penetrated between 948 and 1616 m depth in the Larne No. 2 Borehole, with a temperature at the base of 54 °C (Robins, 1996).

6.3.2 Hydrogeology of the Carboniferous and Devonian cover rocks

There is no information regarding the hydrogeology of Devonian rocks across the region from the depth interval of interest in any of the references reviewed.

There is very limited information regarding the hydrogeology of Carboniferous cover rocks across the region in the depth interval of interest in the references reviewed. However, as the Carboniferous Limestone is a principal aquifer and is locally developed for groundwater there is some information on the hydrogeological characteristics of the unit from the zone of active exploitation, as summarised below.

Carboniferous rocks are exposed mainly in the south-west, within counties Fermanagh, Armagh and Tyrone but it is also found at surface towards Lough Foyle in County Londonderry. Small outcrops are also found at Castle Espie near Comber in County Down. Beneath the Antrim Lava Group, Carboniferous rocks are thought to underlie the Triassic and Permian rocks, based on regional geophysical surveys (Mitchell, 2004). Their extent, thickness and depth is not fully known but are likely to be closer to surface near the margins of the sedimentary basins.

This sequence of rocks comprises up to 3700 m of sedimentary units, ranging from basal conglomerates, limestones of varying degrees of purity, sandstones and shales (Robins, 1996). The degree of cementation in the sandstones is variable but usually high, therefore their permeability tends to be low. Groundwater flow in the shales is mainly associated with faults (Robins, 1996). Flow in the Carboniferous rocks is through fractures and conduits developed by dissolution of the limestone, where it crops out and within 200 m of the ground surface. Some of these Carboniferous limestones (Dartry Limestone (including Knockmore Limestone Member), Ballyshannon Limestone, Ballysteen, Ulster Canal, Cooldaragh and Fearnaght formations) form rocks of high potential groundwater productivity (McConvey, 2005).

The youngest Carboniferous rocks, the Millstone Grit and Coal Measures groups, are found near the towns of Ballycastle and Dungannon. These units contain strata with intergranular permeability but they occupy small areas of ground and have not been exploited for groundwater (Robins, 1996). These are underlain by the Kilskeery and Leitrim groups that comprise conglomerate, mudstone and sandstone, which tend to crop out in upland regions. As a result, they have not been investigated for their groundwater potential, although their potential for groundwater flow is likely to be limited. The mudstones and well-cemented sandstones can confine water in the underlying limestones.

The underlying Tyrone Group contains a mixed sequence of lithologies. Limestones and mudstones form the majority of the succession, underlain by basal clastic red beds. The main limestone units have high productivities and some units are karstic. The upper limestone formations of the Tyrone Group, such as the Glencar and Dartry Limestone formations have developed extensive karstic systems at shallow depths where they crop out, particularly around the flanks of Ballintempo Forest, Belmore Forest and Cuilcagh Mountain in south-west Fermanagh. Extensive mapping and tracing of the karst drainage systems in County Fermanagh have been performed by speleologists to identify the hydraulic connections between potholes and resurgences (Jones et al., 1997), with velocities of 50–300 m/day measured in the Cuilcagh area Robins, 1996).

These limestones are separated from the Ballyshannon Limestone Formation by a thick sequence of marine shales with intercalated coarser-grained sedimentary rocks. The Bundoran and Benbulben Shale formations are separated by the Mullaghmore Sandstone Formation, which is absent in the south of County Fermanagh. Extensive outcrops of these formations are found to the north and south of Lower Lough Erne within the Arney valley and around Ederney, as well as in the south-east of County Fermanagh around the southern and western flanks of Slieve Beagh. Little is known about the groundwater conditions of these formations (Robins, 1996).

The Ballyshannon Limestone Formation is exposed from beneath the upper limestone and shales mainly on either side of Lower Lough Erne. Karstification is known to occur at shallow depths but is not as well developed as it is in the Upper Limestones (Robins, 1996). The Ballyshannon Limestone is underlain by the high-productivity Ballysteen, Ulster Canal, Cooldaragh and Fearnaght formations in south-eastern County Fermanagh (around Lisnaskea), but elsewhere it is underlain by moderately productive rocks. The underlying Clogher Valley Formation that consists of limestone and shale, has been exploited for groundwater between Fivemiletown and Dungannon by boreholes up to 101 m in depth, with artesian conditions sometimes encountered (Robins, 1996).

The basal clastics are of variable lithology, but commonly strongly indurated with poor groundwater potential (Robins, 1996). A mineral exploration borehole near Armagh penetrated 100 m of sandstone. The presence of numerous subvertical clay fault-gouge horizons may restrict groundwater flow (Robins, 1996).

Shallow Carboniferous groundwaters are typically of the calcium bicarbonate type with some waters trending towards sulphate type, particularly where shale horizons are present (Robins, 1996). Artesian groundwater from the Tyrone Group at a depth of 166 m from the 357 m deep Wilson’s Bridge No. 3 Borehole (H 887 476), was relatively fresh with a total dissolved solids content of 445 mg/l (Table 3; Burley et al., 1984).

6.3.3 Hydrogeology of the Silurian and Ordovician basement sedimentary rocks

There is no information regarding the hydrogeology of the Silurian and Ordovician sedimentary rocks of the Longford Down area from any depth interval in the references reviewed.

6.3.4 Hydrogeology of the Ordovician to Precambrian basement rocks and Palaeozoic intrusives

The metamorphic Ordovician to Precambrian basement rocks are found mainly in the north-west but also to a lesser extent in the north-east of the region and typically form high, dissected relief such as the Sperrin Mountains. They include Dalradian Supergroup rocks (of the Sperrin Mountains and north-east County Antrim) and pre-Dalradian rocks (of the Tyrone Central Inlier and Lough Derg Group) (Mitchell, 2004). They are the oldest rocks in Northern Ireland and consist of metamorphosed sedimentary and igneous rocks that have very low porosity and therefore low permeability (Manning, 1971). No evidence regarding the hydrogeological aspects of units in this groundwater system in the depth interval of interest has been identified from the references reviewed.

Groundwater flow, even above the depth of interest, is extremely limited, except where joints are sufficiently dilated (Robins, 1996). The Precambrian rocks do not contain high potential productivity rock formations (McConvey, 2005). Groundwater flow occurs where structural weaknesses are present, such as faults and shear zones (Robins, 1996). Groundwater flows through fractures and seepages appear where these fractures intersect the surface (Robins, 1996). Groundwater, within 200 m of the ground surface, in the Precambrian is of calcium carbonate type, trending towards calcium sulphate type. It is weakly mineralised (mean TDS was about 240 mg/l for 51 samples from Precambrian and intrusive igneous rocks combined) and acidic (Robins, 1996).

There are a number of Palaeozoic felsic igneous intrusions across Northern Ireland. In the centre of the region, the Ordovician Tyrone Igneous Complex consists of gabbro, dolerite and basalt and granite intrusions (Mitchell, 2004). In the south-east of the region within the Southern Uplands–Down–Longford terrane, the late Palaeozoic age Newry Igneous Complex consists of three overlapping granodiorite plutons between Slieve Croob and Forkhill (Mitchell, 2004). In these units, at shallow depths (less than 200 m below the ground surface), groundwater flow is mostly confined to joints and fractures. Groundwater flow follows discrete flow paths from high ground to discharge in nearby streams and rivers (Robins, 1996). No evidence regarding the hydrogeological aspects of units in this groundwater system in the depth interval of interest has been identified from 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 (>15ºC) in the region.

The four groundwater systems are relatively geographically distinct and are primarily separated by major structural lineaments and features. There is no information about the effects that such large-scale structures have on the hydrogeology of the region, consequently it is not possible to assess the nature of any hydrogeological connections between each system. However, some observations can be made regarding hydraulic connection between individual units within the stratigraphically youngest groundwater system:

- There is some hydraulic continuity between the Palaeogene basalts and the underlying Ulster White Limestone at shallow depths (Robins, 1996). However, nested piezometers at Magheramorne and Mullaghglass, near the margins of the basalt, showed that the hydraulic head in the basalt was higher than that in the Ulster White Limestone Formation (Barnes et al., 2003), indicating limited hydraulic connection between the two formations.
- The Mercia Mudstone and Waterloo Mudstone act as confining layers to the underlying Sherwood Sandstone aquifer (Bennett, 1983; Downing et al., 1982) and prevent hydraulic connection with the overlying Cretaceous aquifer.
- The Palaeogene dykes are known to both partially compartmentalise the surrounding country rock (Sherwood Sandstone Group) aquifer and elsewhere act as preferential flow conduits in the Mercia Mudstone (Manning, 1971).
- The 30 m of mudstone separating the Sherwood Sandstone and older Permo-Triassic sandstones in the Ballymacilroy Borehole appears not to act as a barrier to flow, as brines from both sandstones had similar chemical compositions and identical heads (Burgess, 1979).

6.4.2 Anthropogenic pathways

There is a long history of mining, mainly for iron ore, bauxite, coal, lead and salt in Northern Ireland and consequently there is a range of legacy infrastructure. There are relatively few deep (greater than 200 m below NGS datum) boreholes in Northern Ireland, compared with many other regions of similar areal extent in the United Kingdom (Figure 21). These are small clusters of deep boreholes around Lough Neagh, in the Rathlin basin near Ballymoney, and in south-east County Antrim. However, there is no evidence from the reviewed literature of this affecting pathways between the groundwater systems or between groundwater at depth and the near-surface and surface environment.

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

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

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

7.2 GLACIATION

7.2.1 A UK-scale context

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

It is clear from the recent geological record that glaciers have been repeatedly active within the UK landscape over the past two and half million years (Clark et al., 2004; Lee et al., 2011). Numerous periods of glaciation have been recognised, although the scale and extent of glaciers have varied considerably. Most glaciations have been comparatively small (i.e. highland glaciations), although some have been more extensive with glaciers expanding into lowland parts of the UK, i.e. lowland glaciations (Clark et al., 2004; Lee et al., 2011). Over the past half a million years, at least two continental-scale glaciations have affected the UK with ice sheets covering parts of lowland UK, on one occasion as far south as the London area (Figure 17; RWM 2016b; Clark et al., 2004; Lee et al., 2011). Whether glaciations will specifically affect the UK over the next one million years is open to conjecture (Loutre and Berger, 2000). This is because the impacts of global warming and the current melting of the Greenland ice sheet on the long-term climate system are poorly understood, although the general scientific consensus is that the next glaciation has simply been delayed for about 100 000 years (Loutre and Berger, 2000). However, their significance in the recent geological history of the UK coupled with the sensitivity of the UK landmass to climate changes affecting adjacent polar and North Atlantic regions means that their occurrence cannot be discounted.

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

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

7.2.2 A regional perspective

Based upon geological evidence it is widely accepted that Northern Ireland was glaciated extensively during the older part of the last major glacial period (approximately 29 000 to 15 000 years ago: RWM, 2016b; Clark et al., 2012). This glacial period is referred to as the Midlandian Glaciation and is equivalent to the late Devensian glaciation of England, Wales and Scotland (Clark et al., 2012). During this continental scale glaciation, Northern Ireland was glaciated by part of the Last British–Irish Sheet (Shaw et al., 2012; Clark et al., 2012). Geological evidence also demonstrates the presence of a small highland-scale glaciation in the Mourne Mountains during the Younger Dryas (called the Nahanagan Stadial in Northern Ireland), ending just over 11 000 years ago (Wilson 2004). Direct evidence for earlier glaciations in Northern Ireland is absent having been eroded during the Midlandian (Clark et al., 2012). However, the elevation of its highland source areas and the position of Northern Ireland relative to a prominent North Atlantic moisture source (the Gulf Stream) made it highly susceptible to being glaciated.

Over the next million years, it is likely that Northern Ireland will experience highland glaciation and potentially lowland and continental glaciation. During all scales of glaciation, glacial over-deepening of valleys in highland areas may, over multiple glacial cycles, cause the localised lowering of the ground surface into the very top of the depth range of interest (RWM, 2016b). The formation of meltwater-incised valleys beneath glaciers (tunnel valleys) in lowland areas of Northern Ireland 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, over-deepening 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 be affected by isostatic rebound and/or a glacier forebulge during a lowland or continental glaciation which affects an adjacent offshore region (e.g. Irish Sea: RWM, 2016b). This may result in increased fracturing and fault reactivation within the subsurface leading to earthquakes (Loutre and Berger, 2000). The extensive coastline of Northern Ireland make coastal areas of the region susceptible to saline groundwater incursion due either to global sea-level change (driven by global patterns of glaciation) or regional isostasy (RWM, 2016b). Saline groundwater incursion may alter the temporal and spatial patterns of groundwater behaviour (RWM, 2016b).

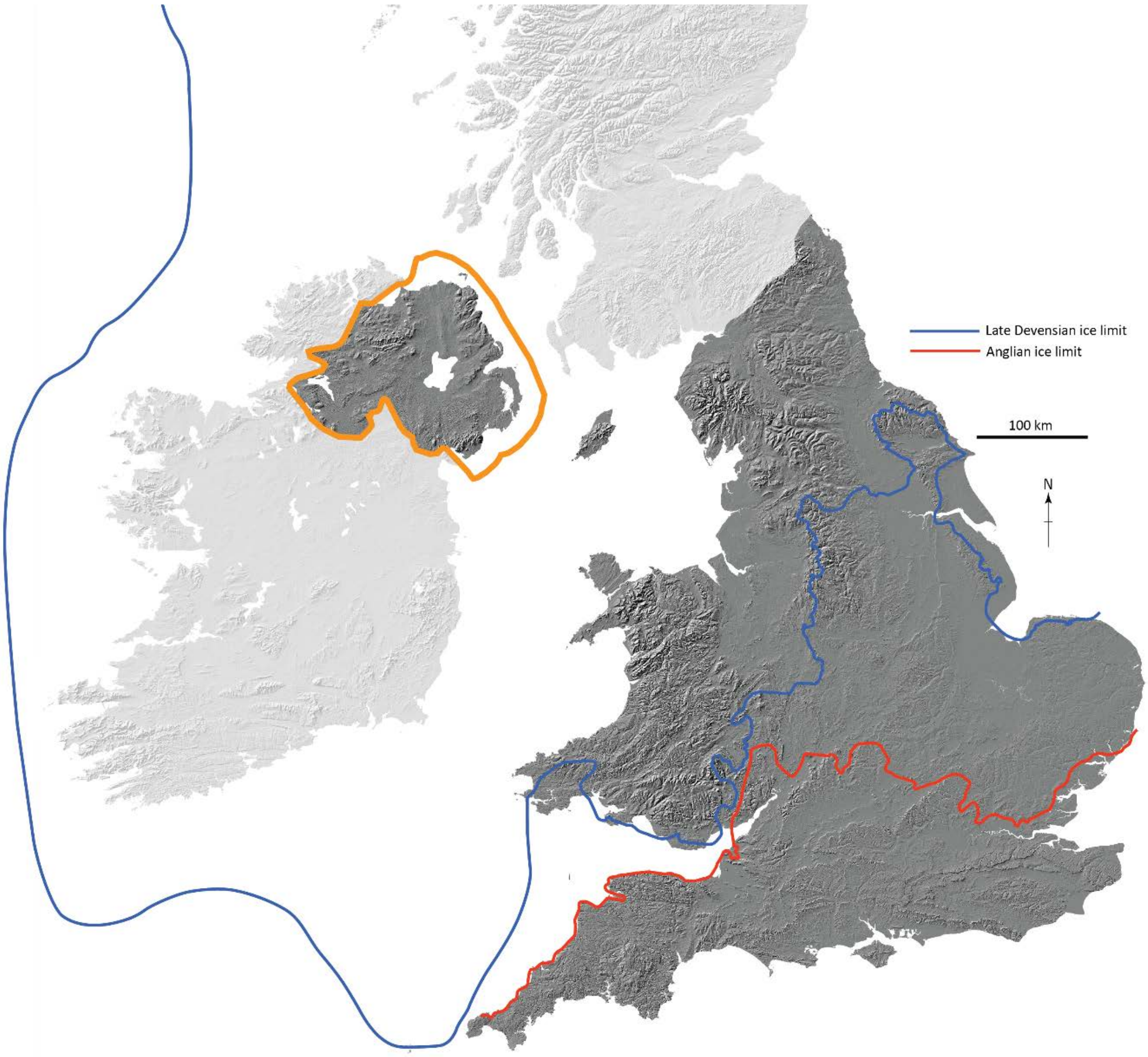


Figure 15 The southern maximum limit of known continental-scale glaciations in the UK over the past 500 000 years during the Anglian (around 480 to 430 ka) and late Devensian (around 30 to16 ka). The location of Northern Ireland is delineated by the orange line. Produced using Copernicus data and information funded by the European Union — EU-DEM layers ©EEA.

7.3 PERMAFROST

7.3.1 A UK-scale context

Permafrost (‘frozen ground’) occurs when the temperature of the ground remains beneath 0°C for at least two consecutive years (French, 2007). Permafrost therefore develops where average air temperatures are much colder than the present day with the 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 15), have all been affected by permafrost as indicated by the extensive weathering of surface geological materials (RWM 2016b). 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 (RWM, 2016b).

Geological evidence demonstrates that all of the UK has been affected by the development of permafrost repeatedly over the past two and a half million years (RWM 2016b). However, evidence for permafrost development is largely associated with shallower parts of 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 Northern Ireland will be subjected to the development of permafrost to a depth of a few hundred metres (Busby et al., 2014). . The development of permafrost can affect groundwater chemistry and behaviour and, in combination with possible localised glacial erosion in highland areas, future development of permafrost may be to several hundred metres beneath the current ground surface (RWM, 2016b).

7.4 SEISMICITY

7.4.1 A UK-scale context

This section contains a description of 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 16). However, earthquakes can also occur within the plates far from the plate boundaries, and where strain rates are low. Such earthquakes are often 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 16). 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 directed 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 structure of the crust and have been the locus 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).

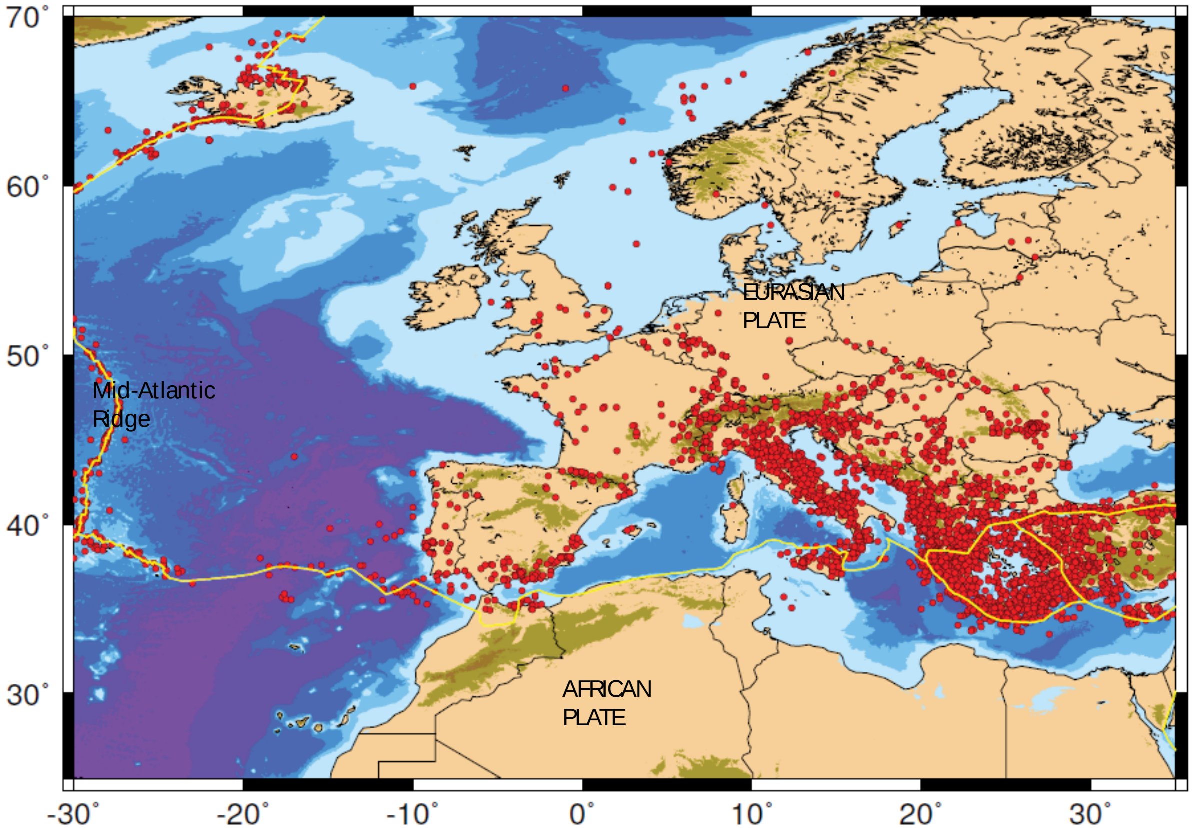


Figure 16 Distribution of earthquakes with moment magnitude greater than 5 across Europe. The earthquakes are from the European Earthquake catalogue (Grünthal and Wahlström, 2012; Stucchi et al., 2013). Topography is from the global model ETOPO1 (Amante and Eakins, 2009). Plate boundaries are indicated by yellow lines.

7.4.2 Seismicity catalogue

The earthquake catalogue used in this project 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 of 4.5 Mw and above that occurred between the years 1700 and 1970, and earthquakes of Mw 5.5 and above that occurred before the year 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 each year (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 local magnitude 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 earthquake with limited numbers of on-scale records (Sargeant and Ottemöller, 2009). Since the beginning of the century, moment magnitude (Mw) has been recommended as a measure of earthquake size and 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):

$$Mw = 0.53 + 0.646\ ML + 0.0376\ ML^2 \quad (1)$$

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 aftershocks) from the earthquake catalogue to leave the main shocks only. In the UK, the number of dependent events of significant magnitude (i.e. > 3 Mw) 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 3 Mw and above. The catalogue for earthquakes smaller than 3.0 Mw 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 1. The catalogue for earthquakes of 3 Mw 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 4 Mw and 5 Mw from 1750 and 1650, respectively. In south-east England, the catalogue extends further back in time (to the 14th century) for earthquakes of 5.5 Mw 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 17 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 British seismicity clearly shows that it is not correlated with the major tectonic structures that bound the tectonic terranes in the UK (Musson, 2007). The terranes are homogeneous in terms of crustal properties (e.g. distribution and style of faulting), but the seismicity within each block is heterogeneous (Musson, 2007). There are spatial variations in the level of seismic activity across the UK. Western Scotland, western England, Wales, south-western Cornwall, and the area off the coast of the south-eastern England are the areas of highest activity. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free (Figure 17).

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

The largest earthquake in the catalogue is the 7 June 1931 Mw 5.9 event in the Dogger Bank area (Neilson et al., 1984). This is the largest UK earthquake for which a reliable magnitude can be estimated. The largest onshore instrumental earthquake in the UK is the 19 July 1984 Mw 5.1 event near Yr Eifel in the Lleyn Peninsula. Its hypocentre was relatively deep with a focal depth of around 20 km (Turbitt et al., 1985). The event was followed by a prolonged number of after shocks including a Mw 4.0 event in 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).

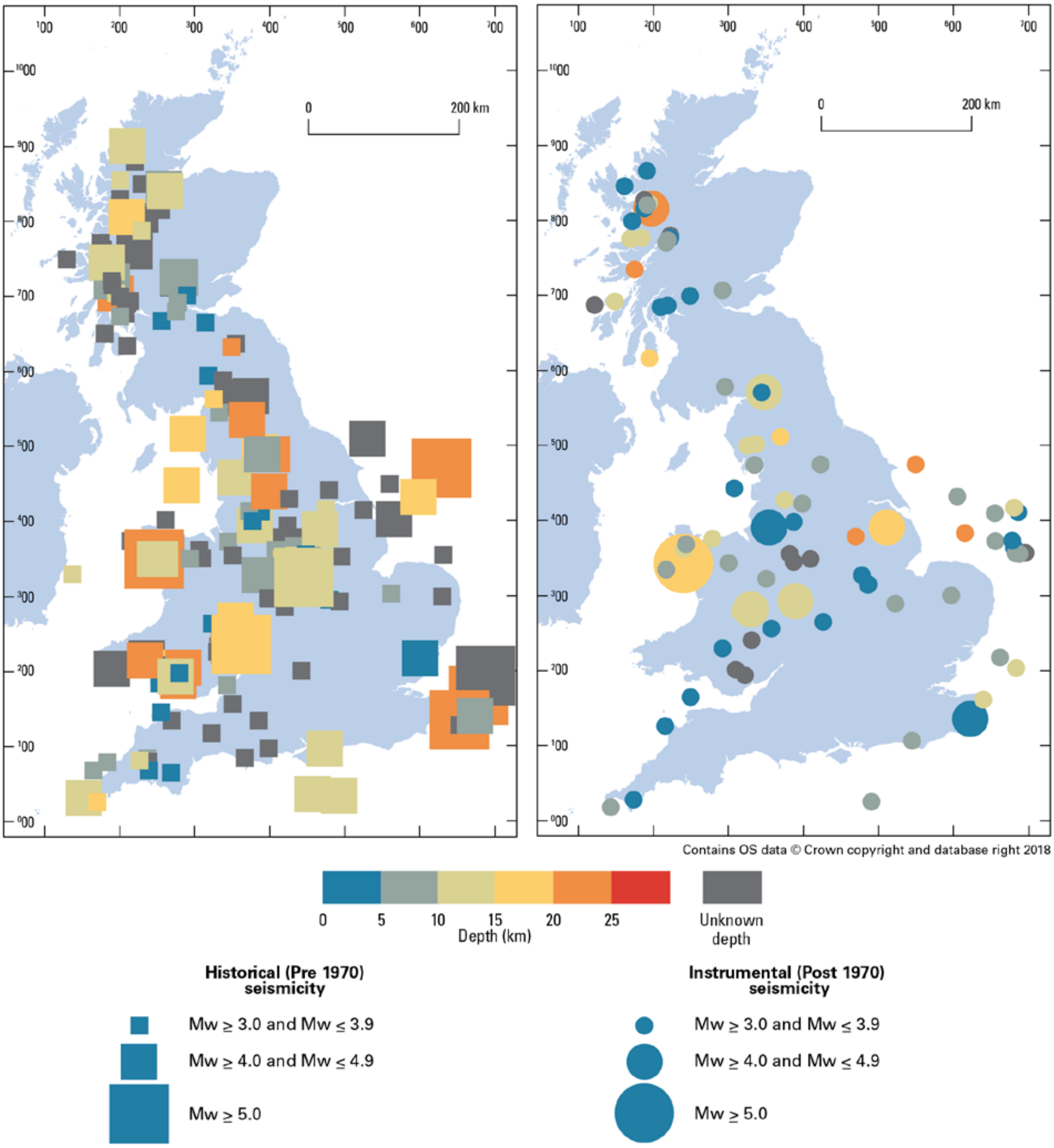


Figure 17 Distribution of the main shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological 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 1–2 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 18 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, the 19 July 1984 Mw 5.1 Lleyn earthquake) tend to occur at greater depths (Figure 18).

Earthquakes with magnitudes of around 5 Mw 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 6.0 Mw 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.

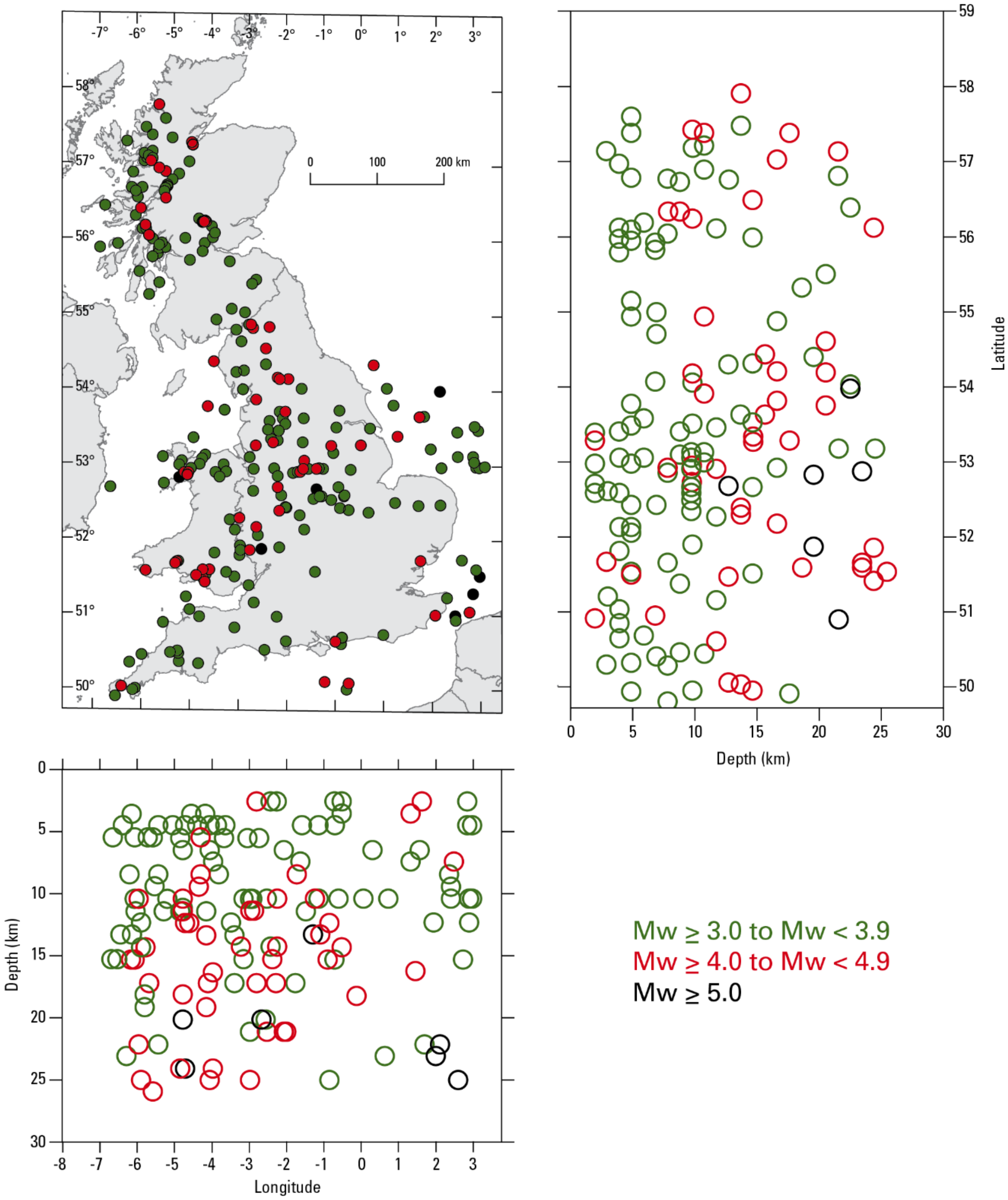


Figure 18 Relationship between the focal depth and the geographical distribution of the mains shocks with Mw ≥ 3.0 in the UK. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost

earthquake-free. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290. Contains British Geological Survey digital data © UKRI 2018

7.4.4 Maximum magnitude

The largest earthquake in the BGS earthquake catalogue has a magnitude of 5.9 Mw (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 (7 Mw) 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 6.0 Mw, considering the absence of any evidence for an earthquake above 6.0 Mw in the last 1000 years. For onshore seismicity the historical limit could be set even lower, around 5.5 Mw because historical onshore earthquakes have never been larger than 5.1 Mw (Musson, 2007; Musson and Sargeant, 2007). However, there is palaeoseismic evidence from Belgium for prehistoric earthquakes between 6.5 and 7.0 in magnitude (Camelbeeck and Megrahoui, 1996; Camelbeeck, 1999). Therefore, we cannot rule out the occurrence of an earthquake that may have a larger magnitude than the largest magnitude observed in the British seismicity catalogue and may have occurred before the beginning of the historical catalogue.

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

$$\text{Log } N = a - b\,\text{M} \qquad (2)$$

where N is the number of earthquakes per year greater than magnitude M. 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 1) 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 = 3.266–0.993 M. This is roughly equivalent to an earthquake occurring somewhere in the British Isles with a magnitude of 5 Mw 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 6.0 Mw 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:

1. The duration of the earthquake catalogue (~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.
2. 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 sources of uncertainties.

7.4.8 A regional perspective

The regional perspective for Northern Ireland (Figure 19) shows the earthquake activity, or lack of earthquake activity, in Northern Ireland. This is not due to a deficiency of data and the reasons for the relative absence of earthquakes in Northern Ireland are poorly understood (Musson, 2007). However, earthquakes in western Scotland (e.g. 1880, Mw 4.9 Argyll earthquake) have been felt also in Northern Ireland (Musson, 1996).

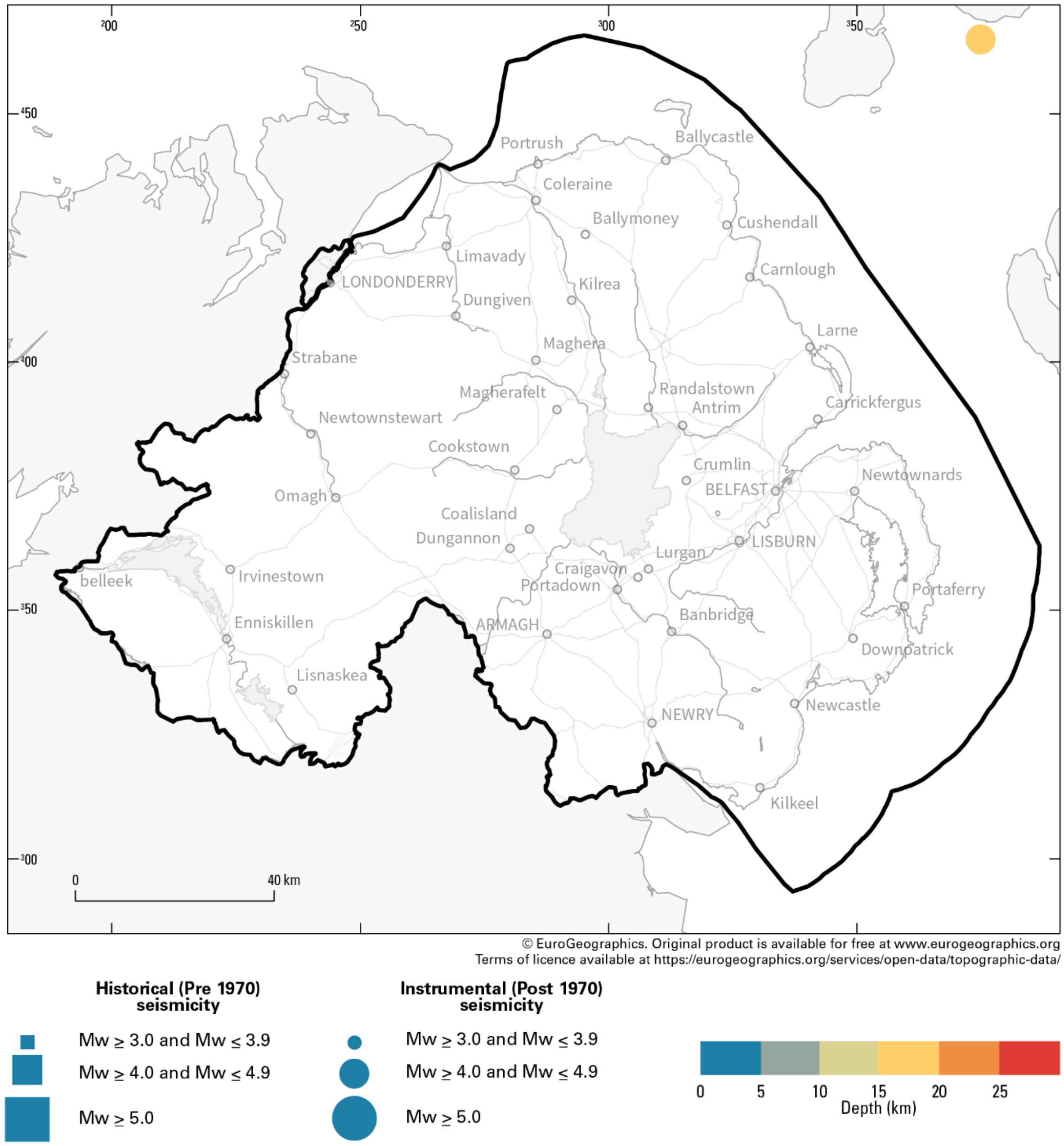


Figure 19 Historical and instrumentally recorded earthquakes in Northern Ireland. The symbols are scaled by magnitude and coloured by depth. Contains EuroGeographics data ©EuroGeographics. Contains British Geological Survey digital data © UKRI 2018

8 Screening topic 5: resources

8.1 OVERVIEW OF APPROACH

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

This section explains what is known of mineral resources in Northern Ireland. 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

Also considered are geothermal energy, unconventional hydrocarbon resources and areas suitable for gas storage. 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 are 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 has been sourced from a wide range of already existing BGS datasets and the relevant data has 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 study a review of BGS memoirs, which lists historic workings, was required. An important consideration in the assessment of all these resources was the depth as to which they occur or the depth 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 Database 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 NORTHERN IRELAND

The distribution of mineral resources in the Northern Ireland region is shown in Figure 20. Northern Ireland has a long history of mining, mainly for iron ore, bauxite, coal, lead and salt. Most of this mining activity had ceased by the middle of the 20th century and there is now only one active salt mine in County Antrim and an opencast gold mine in County Tyrone that was operating until recently. Two small coalfields were extensively mined in the 18th and 19th centuries but there is little economic potential for further extraction. There are no producing oil or gas fields in Northern Ireland although recent exploration has indicated that there may be significant resources to be discovered. Recent exploration for metalliferous minerals has been focussed on gold and there are plans for the development of two underground mines in County Tyrone. There are plans to develop salt caverns for natural gas storage and compressed air energy storage (CAES) in south-east County Antrim.

8.3 COAL AND RELATED COMMODITIES

The two small coalfield areas around Coalisland, County Tyrone and Ballycastle, County Antrim are exposed at the surface and historically, surface workings were succeeded by underground mining. Mining ceased in the 1930s at Coalisland, reaching depths of around 270 m below NGS datum, and in 1967 at Ballycastle. There may be more extensive coal resources in the deeper parts of the Lough Neagh and Rathlin sedimentary basins, although these would be beyond the reach of conventional mining and their main significance would be as potential petroleum source rocks.

8.4 POTASH, HALITE, GYPSUM/ANHYDRITE AND POLYHALITE DEPOSITS

Salt deposits of Permian and Triassic age appear to be restricted to the Larne sedimentary basin in Northern Ireland, although there is no borehole information from the deepest parts of the Lough Neagh and Rathlin basins to confirm this.

Historically Triassic halite was mined in the south and east of County Antrim, using both conventional extraction and solution brining. There is currently one active salt mine at Kilroot, near Carrickfergus which has a maximum depth of around 400 m and around 2 km^2 of workings. The current workings are accessed from a surface portal and boreholes outside this area have proved salt down to at least 300 m below NGS datum.

8.5 OTHER BEDDED AND MISCELLANEOUS COMMODITIES

Iron ore and bauxite occur in the Interbasaltic Formation of the Palaeogene Antrim Lava Group. They formed as the result of a process of laterisation during a long period of subtropical weathering in the hiatus between the eruption of the Lower Basalt and Upper Basalt Formations. The iron ore was worked extensively from the 18th century through to the 1920s with bauxite produced mainly as a by-product. During the Second World War more intensive mining of bauxite took place at Lyle’s Hill, Ballybarnish, Elginny and Skerry West, County Antrim, when 296 000 tons of bauxite were extracted and used to produce aluminium for the war effort. Mining ceased in December 1945 and small quantities of bauxitic clay are now extracted from only one locality in County Antrim at Clinty Quarry. The Interbasaltic Formation is subhorizontal and was accessed by adits driven into the valley sides and therefore was not worked deeper than 100 m below NGS datum. A number of other commodities have been mined at shallow depths in Northern Ireland.

8.6 VEIN-TYPE AND RELATED ORE DEPOSITS

Lead was mined in the 18th and 19th centuries around Keady, County Armagh (shown on Figure 20 as the Armagh–Monaghan mining district) and near Newtownards, County Down, where the Conlig Mine was one of the major lead mines in the UK during the 19th Century. The Newtownards vein deposits were accessed from adits and shafts from shallow depths down to about 350 m below NGS datum. Because of the widespread distribution of mineral veins and the extent of past shallow mine workings in these areas they may be re-examined in future for mineral resources.

More recent exploration has identified strata-bound, base-metal mineralisation in the Dalradian Supergroup and the Tyrone Volcanic Group, all within the Sperrin Mountains of County Tyrone. Drilling has shown that copper, lead and zinc mineralisation occurs at depths greater than 100 m below NGS datum in this area. The early Carboniferous sedimentary rocks of counties Fermanagh and Tyrone may be prospective for base-metal resources adjacent to major faults in a setting analogous to that of the major lead–zinc orefield of the Irish Midlands (e.g. Navan, County Meath).

8.7 PRECIOUS METALS

Gold occurrences in Ireland have been known since prehistoric times but no historical mining is recorded. Since the early 1980s there has been a considerable exploration effort which has led to the discovery of two significant gold deposits within Dalradian Supergroup metasedimentary rocks at Cavanacaw and Curraghinalt, County Tyrone. Gold and silver has been extracted by opencast working at Cavanacaw and planning permission has been granted to develop an underground mine. Drilling has proved that gold-bearing veins extend at least 300 m below NGS datum. Mine feasibility studies and underground bulk sampling are currently being carried out on the Curraghinalt deposit and mineralised intersections have been recorded over 400 m below NGS datum.

Recent exploration has identified gold mineralisation associated with the Orlock Bridge Fault juxtaposing the Ordovician and Silurian rocks of the Longford–Down part of the Southern Uplands terrane. In Northern Ireland significant gold intersections have been recorded from the area near Clay Lake, County Armagh, and along strike at Clontibret, County Monaghan, drilling has proved intersections down to over 200 m below NGS datum.

8.8 HYDROCARBONS (OIL AND GAS)

There are no proven conventional oil or gas fields onshore Northern Ireland or within the waters adjacent to Northern Ireland. However, recent exploration indicates that the Rathlin, Larne and Lough Neagh sedimentary basins, which are largely concealed beneath the thick basalts of the Palaeogene Antrim Lava Group, have the potential to contain significant accumulations of hydrocarbons within Triassic, Permian or Carboniferous sandstone reservoirs. Reservoir targets may range from about 1000 m to 2500 m depth below NGS datum.

In County Fermanagh, in the Irish north-west Carboniferous basin, gas shows have been recorded in exploration wells drilled since the 1960s but with no commercially viable flows. The Mullaghmore Sandstone Formation and the Bundoran Shale Formation may have some tight gas and shale gas potential, respectively, within a depth range of about 900 m to 1500 m below NGS datum.

8.9 GAS STORAGE

There are two projects to develop compressed air energy storage (CAES) and natural gas storage caverns in Permian age salt on Islandmagee near Larne, County Antrim. Recent seismic surveys and drilling results indicate that the salt bed is over 200 m thick beneath the northern part of Larne Lough, although onshore thick Permian salt may be restricted to a small area of about 50 km^2 which probably extends offshore into the North Channel. The Permian salt occurs at depths of 1400 to 1800 m below NGS datum.

8.10 GEOTHERMAL ENERGY

Ground-source heat-pump technology can be deployed in most areas of Northern Ireland to extract shallow geothermal energy for heating and cooling purposes. The potential for deep geothermal energy is more restricted, but the sandstone reservoir units that are the hydrocarbons exploration targets in the Rathlin, Larne and Lough Neagh sedimentary basins also have potential as geothermal aquifers, at least for direct heating applications. The high heat production granites of the Palaeogene age Mourne Mountains Complex could have enhanced geothermal systems (EGS) resource potential in the future, as EGS technology matures.

8.11 HIGH DENSITY OF DEEP BOREHOLES

There are relatively few deep (greater than 200 m below NGS datum) boreholes in Northern Ireland, compared with many other regions of similar areal extent in the United Kingdom (Figure 21). These are small clusters of deep boreholes around Lough Neagh, in the Rathlin basin near Ballymoney, and in south-east County Antrim. Exploration for lignite beds in the Oligocene Lough Neagh Clays Group has taken place to the west, south and east of Lough Neagh and near Ballymoney. To the south-west of Lough Neagh deep boreholes were drilled to evaluate the possible extension of the east Tyrone coalfields. In south-east Antrim there is a cluster of deep boreholes drilled to investigate the extent of Permian and Triassic salt beds at depth. Recent exploration for gold in the Sperrin Mountains has included quite intensive deep drilling in a small area around the Curraghinalt gold deposit.

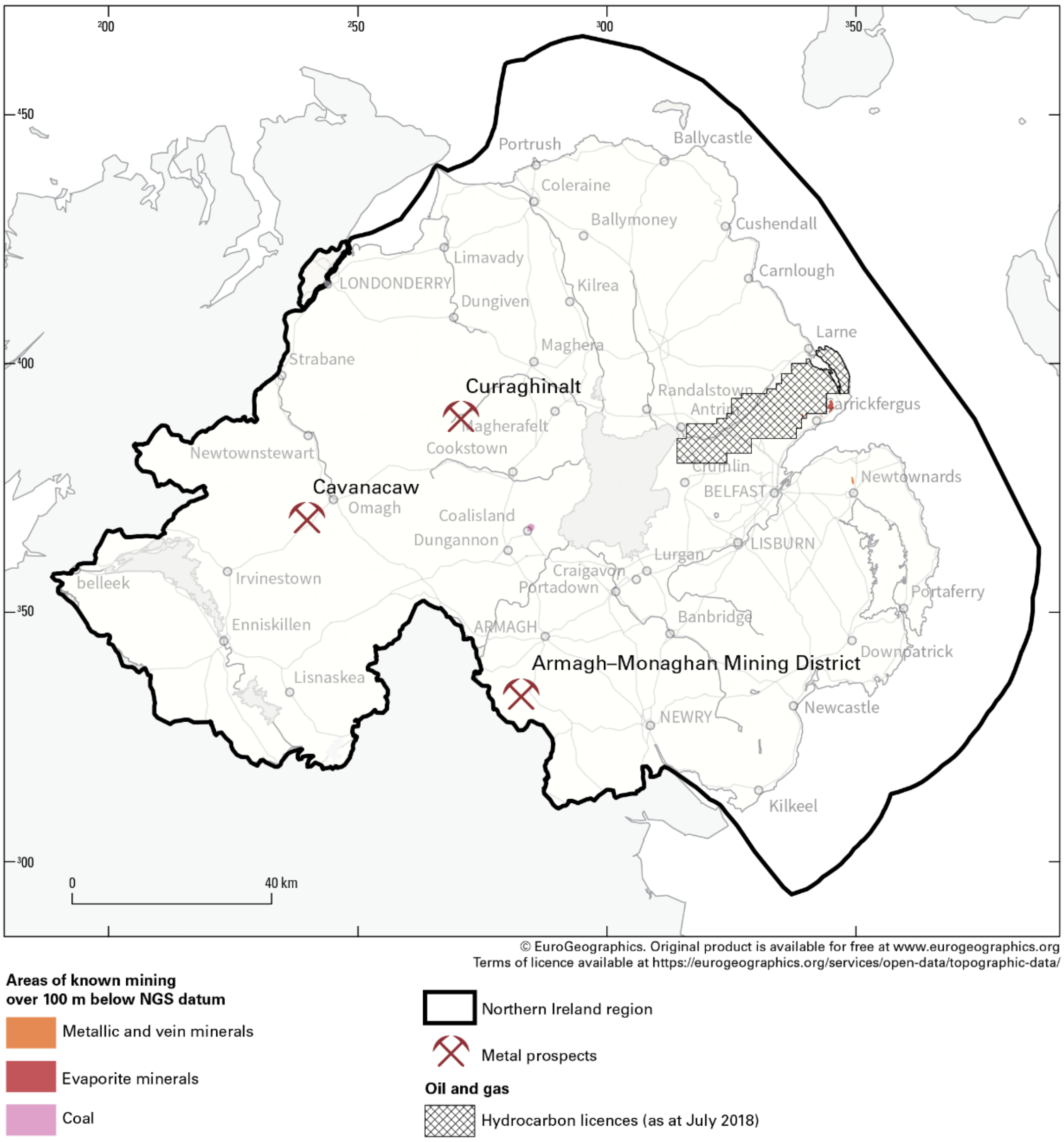


Figure 20 Distribution of mineral resources in Northern Ireland. The hydrocarbon licence areas represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place. Depleted oil and gas fields and underground gas storage licence areas are not shown. Contains EuroGeographics data ©EuroGeographics. Contains British Geological Survey digital data © UKRI 2018

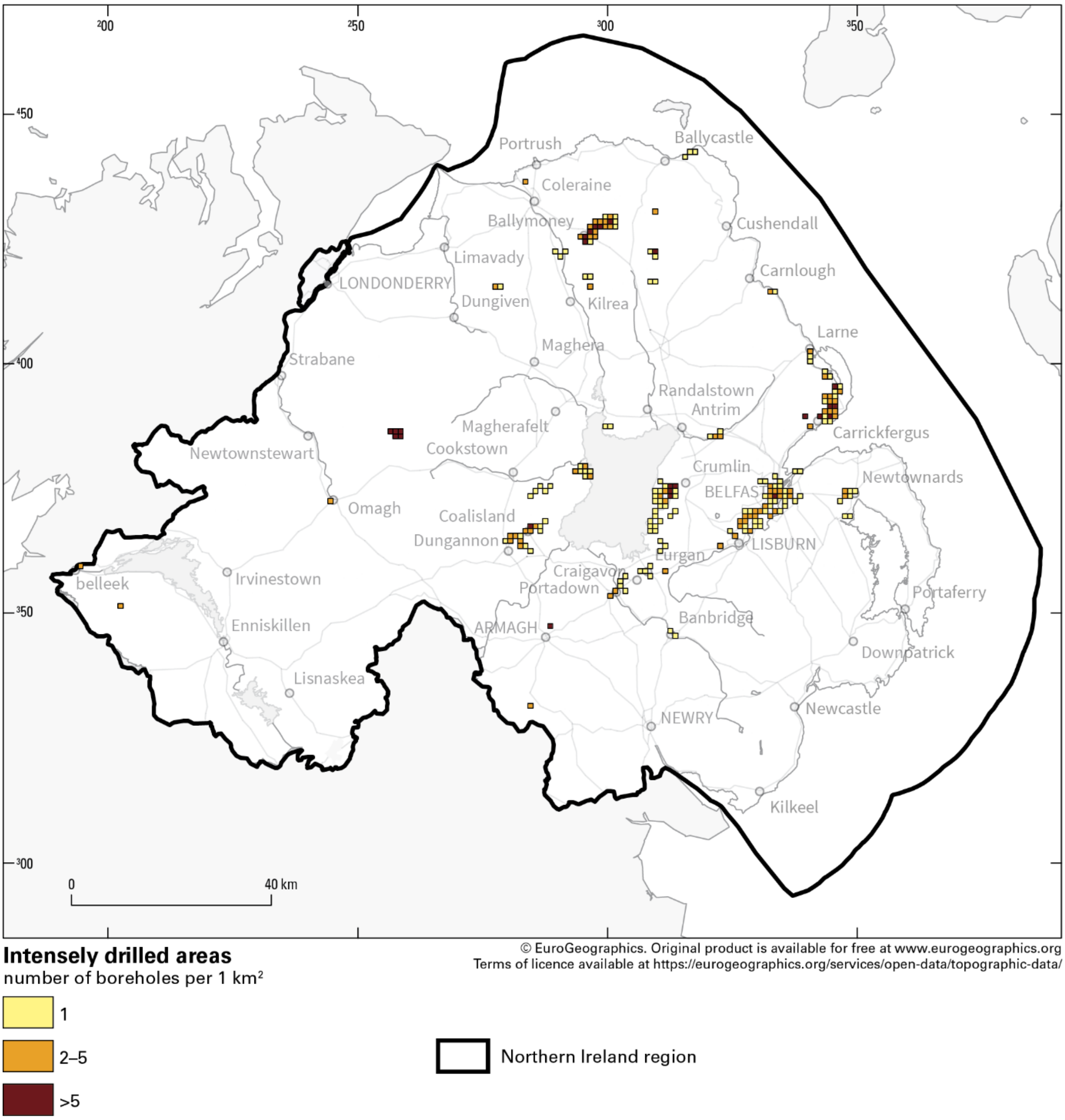


Figure 21 Location of intensely drilled areas in Northern Ireland, showing the number of boreholes drilled per 1 km^2 that penetrate greater than 200 m below NGS datum. Contains EuroGeographics data ©EuroGeographics. Contains British Geological Survey digital data © UKRI 2018

8.12 SUPPORTING INFORMATION

8.12.1 Mine depths

Reported mine depths are often difficult to attribute to specific datums. For example depths are variously reported from surface or adits but it is often unclear which is being used and in which area of a mine, without undertaking significant research that may need to include examination of old mine plans. A pragmatic solution to this issue has been to assume that depths are below deepest adit unless otherwise stated. Adits were driven from nearby valleys so another reasonable assumption is that adit level is approximately equal to NGS datum at the mine site.

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

Depth calculations based on these assumptions will tend to be conservative and to slightly overestimate maximum depth.

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 mines 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 m

Depths in metres have been rounded to 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 overestimate depth.

8.12.2 Mined extents

The areas of vein-type and related ore deposits shown in Figure 20 have been depicted where possible by applying a 100 m wide buffer to the mapped vein and where this is not possible, by applying a buffer to the mine location that encompasses the extent of the workings. This approach ensures that any inaccuracies in the mapped vein locations and extent of past workings and dips in the vein structures are within the area identified.

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

8.12.3 Potash, halite, gypsum/anhydrite and polyhalite deposits

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

8.12.4 Hydrocarbons (oil and gas)

The hydrocarbon licence areas displayed in Figure 20 represent all valid licences for exploration, development or production. The presence of a licence is no indicator that resources may be present or extraction will take place.

In Northern Ireland there has been limited exploration for hydrocarbons and the overlying basalts reduce ability to image and map the target reservoirs in the Rathlin, Lough Neagh and Larne basins and thus the location, extent and depth of conventional hydrocarbon reservoirs is not well constrained. Conversely, the extents, depths and contained resource of unconventional (shale) gas and oil deposits is less well constrained. The distribution of the prospective rock types is based on geological factors (see Rock type for discussion on these) and the potential of this type of deposit in any particular location is dependent on a number of factors such as past burial depth, organic content of the rocks and the practicality of extraction, none of which have been evaluated in the region.

8.12.5 Coal and related commodities

In many coal-mining areas the coal seams are associated with other commodities that may also have been worked underground from the same mines, either with the coal or from separate layers. 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 depths 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 extent of older coal workings are 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 depths and distribution of deep unworked coal because this has not been mined. In many areas it is constrained by information from seismic surveys and boreholes that were undertaken to assess coal resources and thus is well constrained but this is not the case in Northern Ireland.

8.12.6 Borehole depths

Not all boreholes are drilled vertically, with some, mainly for mineral exploration, inclined and a few, mainly for hydrocarbon exploitation, deviated. The GSNI boreholes databases record borehole length and not vertical depth, unless specifically stated. For the purposes of preparing the borehole map (Figure 21) 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 overestimate maximum depth. 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 a few cases this is to the nearest one-kilometre 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 the digital capture of locations developed more precise grid references were recorded to capture any associated uncertainty. A precision field in the data table is used to indicate the certainty with which the grid reference was determined (e.g. 'known to nearest 10 m').

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Resources

Borehole locations

The locations of deep boreholes are from the GSNI borehole database.

Other bedded mineral resources

Locations of operating and abandoned salt mines are taken from mine plans and GSNI records.

Hydrocarbon resources

The locations of onshore petroleum licences are available via the Department for Energy website https://www.economy-ni.gov.uk/publications/petroleum-licence-map and for offshore petroleum licences via the OGA website https://www.gov.uk/guidance/oil-and-gas-offshore-maps-and-gis-shapefiles