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A Study of Potential Unconventional Gas Resource in Wales

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A Study of Potential Unconventional Gas Resource in Wales

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British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276

email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD

Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

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Summary

This report was commissioned by the Welsh Government (Energy, Water and Flood Division) to provide information on unconventional gas in Wales. The main aims were to identify areas of Wales, onshore and immediately offshore, where unconventional gas resources may be found at depth and summarise published estimates of gas-initially-in-place (GIIP). This study also contains outline information on methods for exploration and development of unconventional gas resources; potential impacts on environment and health; and limitations of existing knowledge.

This report does not make any new reserves or resource estimates as we consider that there is presently not enough publically-available data available on the geology, engineering or associated costs of production to make reliable estimates at this stage. Estimates will only be developed with information derived from increased exploration and further research in the future.

Potential unconventional gas resources in Wales are most likely to be found in association with coal seams or shales. Unconventional gas is natural gas which is trapped in rocks which have a low permeability and require engineering intervention such as hydraulic fracturing to allow the gas to flow into the wellbore.

Unconventional gas from coal includes Coal Bed Methane (CBM), Abandoned Mine Methane (AMM), Coal Mine Methane (CMM), and Underground Coal Gasification (UCG). The legacy of coal mining in Wales has generated an extensive archive of information describing the structure and composition the coalfields. This information is held by the British Geological Survey (BGS) and Coal Authority. Based on analysis of these data, the BGS produced a review of unconventional gas from coal, commissioned by the Department of Trade and Industry, that estimated a potential resource within the south Wales coalfield as almost 290 bcm (billions of cubic metres) (Jones et al., 2004). There are a number of other studies, presented in this report which point to CBM resource (all of the figures are as quoted by the individual operators): IGas predict between 1,095 and 3,243 bscf (Billions of standard cubic feet) of CBM resource offshore from Point of Ayr; Eden Energy Ltd give an estimate of between 687-1363 bcf (billions of cubic feet) across their licence areas in south Wales; Dart Energy Ltd have licence areas in north and south Wales. Their licence area near Swansea is reported to contain between 320 and 750 bcf for CBM.

Interest in shale gas in the UK has so far centred on areas of England where there is a high density of existing subsurface geological data, mostly provided by conventional hydrocarbon exploration. Some of this data contributed to a report commissioned by DECC and published in 2013, which gave gas-in-place resource estimates (not proven to be recoverable) for the Bowland-Hodder unit, of northern England, as between 23.3 and 64.6 tcm (882 and 2281 tcf).

Despite a relative paucity of these data in Wales, a number of Petroleum Exploration and Development Licences (PEDL) have been granted by the Department of Energy and Climate Change (DECC). Interest in Wales has focused on the middle Carboniferous shales underlying the coalfield strata of north and south Wales and a number of preliminary resource estimates have been published by the license holders. Dart Energy Ltd estimated 30,550 bcf of gas-in-place for middle Carboniferous shales underlying its licences across Wrexham and Cheshire. Eden Energy Ltd published an upper estimate of 34.198 tcf GIIP (trillions of cubic feet gas-initially-in-place) for the equivalent geological horizon, for its licence areas in south Wales. There are other geological units discussed in this report which may have potential for shale gas in Wales, including the early Carboniferous shales (Avon Group) and the carbonaceous mudstones of Lower Palaeozoic age. The limited geological information available makes accurate forecasts of potential resources difficult, a situation which will be improved by new data derived from commercial exploration.

The recent environmental review undertaken by DECC (Department of Energy and Climate Change, 2013b) stated that “the likely significant environmental effects of activities following further onshore oil and gas licensing have been identified, described and evaluated in order to comply with the Strategic Environmental Assessment Directive (2001/42/EC)”. The environmental review considered a range of environmental and health impacts. These impacts include the following which are also described in this report: sourcing water for drilling and exploration; the potential for pollution; seismic hazards associated with hydraulic fracturing; and naturally occurring radioactive material (NORM). The environmental review undertaken by DECC goes on to say that “through the use of construction and operation best practice, environmental effects resulting from licensing of onshore exploration and production activities could be minimised and managed to be acceptable to regulators, decision makers and communities”.

1 Introduction

In 2012, the Welsh Government published a report called “Energy Wales: A Low Carbon Transition” which sets out its aspiration towards a low carbon energy system. The report stated that “gas will be a transitional fuel because greenhouse gas emissions from gas are less than that from coal and as a flexible, responsive and reliable source of energy, gas can play a key role in the transition to a low carbon energy system” (Welsh Government, 2012b). Because of its importance as a transitional fuel, there is a clear need to understand the resource potential and impacts of developing indigenous unconventional gas resources.

Conventional oil and gas is crude oil and natural gas that is produced by a well drilled into a geologic formation in which the reservoir and fluid characteristics permit the oil and natural gas to readily flow to the wellbore (Energy Information Administration, 2014). A common characteristic of unconventional gas is that it is trapped in rocks with a low permeability, requiring engineering intervention such as hydraulic fracturing to allow the gas to flow. Unconventional gas resources in Wales fall into two categories: gas associated with coal and gas associated with shale.

Coal is widely distributed around the world with an estimated proven reserve of 984 billion tonnes (World Coal Institute, 2005). The biggest reserves are in the USA, Russia, China and India. Many of these coals will contain methane in commercial quantities. Al-Jubori et al. (2009) list Russia, USA, China, Australia, Canada, UK, Ukraine and Kazakhstan as having major CBM reserves (Table 1).

Estimates of CBM resources vary: Creedy (1999) estimated that there were 2,450 bcm of CBM in the UK. Jones et al. (2004) subsequently estimated the total CBM resource in the UK to be 2,900 bcm. In the USA, CBM developments achieve recovery factors of 30-40% in some fields. Assuming a 10% recovery factor in the UK, this would amount to 290 bcm which equates to three years of UK natural gas supply (Department of Energy and Climate Change. 2010b).

Rank	**Country**	**Volumes (trillion cubic feet)**
1	Russia	1730
2	China	1307
3	Alaska	1037
4	Australia	1037
5	USA minus Alaska	711
6	Canada	966
7	UK	102
8	India	71
9	Ukraine	42
10	Kazakhstan	23

Table 1 Top 10 countries with technically recoverable coalbed methane resources (Al-Jubori et al. 2009)

Rank	**Country**	**Volumes (trillion cubic feet)**
1	China	1115
2	Argentina	802
3	Algeria	707
4	US	665
5	Canada	573
6	Mexico	545
7	Australia	437
8	South Africa	390
9	Russia	285
10	Brazil	245

Table 2 Top 10 countries with technically recoverable shale gas resources (Energy Information Administration, 2013)

Gas from coal is generally well-understood, an understanding built up through decades of exploitation of the indigenous coal resource. Knowledge of the geology of the coalfields is based on the legacy data from the coal mining industry. The coal industry and mapping by the British Geological Survey provided a wealth of information on the individual coal seam thicknesses, their distribution and geological structure. The historical knowledge derived has also shown in which areas seams are likely to be gassy as well as providing valuable coal chemistry data. A comprehensive review of Coal methane in Wales was undertaken by the BGS for the DTI (Jones et al., 2004). There are also a number of studies, undertaken by commercial companies which focus on small areas within the coalfields. Key aspects of these are presented in Section 2.4.

The shale gas industry globally, in contrast, is in its infancy with estimates of volumes of gas being constantly refined. The Energy Information Administration (Energy Information Administration, 2013) identified and assessed shale gas resources in 41 countries and estimated a technically recoverable resource of 7,299 trillion cubic feet of gas. The top ten countries with technically recoverable resources are shown in Table 2.

Estimates available for the volume of shale gas in the UK vary considerably. A report prepared for DECC in 2010 indicated that the UK shale gas reserve could potentially be 150 bcm (5.3 tcf) but stressed that research into shale gas in the UK is in early stages, and ahead of drilling, hydraulic fracturing and flow testing, the estimate may prove to be invalid (Department of Energy and Climate Change, 2010a). A subsequent report commissioned by DECC and published in 2013 gave gas-in-place resource estimates (not proven to be recoverable) for the Bowland-Hodder unit, of northern England, as between 23.3 and 64.6 tcm (Andrews 2013a).

Outside the coalfields, there has been very little exploration for conventional or unconventional hydrocarbon resources in Wales to date. This has led to a paucity of subsurface data against which to evaluate potential resources of shale gas. Further research will be needed into potentially prospective rock units. This will need to include drilling and analysis of boreholes and, potentially the acquisition of seismic reflection data, in order to better understand Wales' shale gas potential (Section 3). For example, the Utica Shales of North America and also the Bowland-Hodder unit of northern England are both prospective for shale gas in America and northern England respectively. In Wales, although there are known to be shale units of similar age, there is, as yet, insufficient information available to assess whether a shale gas resource is present or to estimate the quantity of any gas.

This report is a summary of the current state of geological knowledge of unconventional gas and its potential distribution in Wales. Coalbed methane, abandoned mine methane, coal mine methane, underground coal gasification and shale gas are defined, and a summary of their mechanisms of formation and their potential distribution is provided. Summary information on how gas is extracted and, where appropriate, a history of its exploration is also presented. Resource estimates published by individual exploration companies, where available, from licensed areas (Appendix 1) are also given but not verified. These estimates are shown using precise technical terminology. In order for these to be understood and compared, a description of relevant terminology used in resource and reserves estimates is given in Appendix 1.

This report does not make any new reserves or resource estimates as we consider that there is presently not enough publically available data available on the geology, engineering or associated costs of production to make reliable estimates at this stage. Estimates will only be developed with information derived from increased exploration and further research in the future.

2 Unconventional gas resources from coal

2.1 ORIGIN OF COAL AND METHANE

The origin of coal

Coal is the remains of prehistoric vegetation that has accumulated into thick deposits of organic matter (peat) in swamps and peat bogs. When peat is buried beneath other sediments in sedimentary basins (subsiding areas of the Earth's crust) over geological time, it becomes compressed by the weight of the overlying strata. With increasing depth, it also heats up, because heat from the Earth's core flows outwards towards the ground surface and so rocks in the subsurface get hotter as they become more deeply buried. The heat and pressure results in water and gases (mainly methane) being driven out of the peat which, as it is progressively buried, is converted first to lignite and then to coal. Because it is derived from organic matter, coal contains a high proportion of carbon and it consists largely of organic carbonaceous molecules. As heat and pressure on the coal increase, and methane and water are driven off, the proportion of carbon in the coal increases and it is said to increase in rank (Bloxam et al., 1985, Gayer, 1999). Rank increases in the order: lignite, sub-bituminous coal, bituminous coal, semi-anthracite, anthracite. Bituminous coals are commonly subdivided into steam coals and (higher rank) metallurgical coals which are used for coking.

Although we generally think of coal as a solid, essentially impermeable substance, it does contains microscopic pore spaces. Also, bituminous coal seams typically contain one or more sets of sub-parallel near-vertical fractures known as cleats. Typically there are two sets of cleat in a coal seam at approximate right angles to each other. The dominant set of cleats, which cuts across the other set, is known as the face cleat. The other set is known as the butt cleat. Under favourable circumstances the cleats can impart some permeability to coal, allowing water and gases to flow along it. Figure 1 shows a piece of coal with well-developed cleat: the surface facing the viewer is a face cleat, the horizontal fractures are bedding within the coal and the fractures apparently going into the page, at 90° to the face cleat, are the butt cleat.

Figure 1 Cleat in coal

Coalbed methane

As methane is driven off coal during the coalification process, some of it remains behind because it becomes adsorbed onto (carbonaceous) molecules that line the micropores within the coal and the cleat. It is held in place against the carbonaceous molecules by electrostatic forces (these are much weaker than chemical bonds - they can be overcome by heating the coal or reducing the pressure). The methane held in this way in coal seams is referred to as coalbed methane in the oil and gas industry. It is exactly the same methane that is known as firedamp in the mining industry. In the mining industry firedamp is liberated from the coal seams into the mine workings because the pressure within the coal seams in their unmined state is reduced to atmospheric pressure by mining, which allows the methane to desorb from the coal and into the mine workings (Jones et al. 2004).

Coal bed methane (CBM) typically comprises 80-90% methane, 0-8% ethane, 0-4% propane and other hydrocarbons with 2-8% nitrogen and 0.2-6% carbon dioxide with trace amounts of argon, helium and hydrogen (Creedy, 1991).

Production of conventional gas and coalbed methane

In the oil and gas industry, coalbed methane is referred to as an unconventional gas because it is not recovered in the same way as so-called conventional gas (for example North Sea gas) which exists in a free state in the pore spaces between the grains of reservoir rocks such as sandstones (conventional gas is not adsorbed onto the sides of the pore spaces of the reservoir rocks in which it is found).

Fluids (liquids and gases) in the subsurface, at the depths at which conventional gas is found, are generally under significantly greater than atmospheric pressures. For the purposes of describing how such fluids are pressurised, the rocks that occur beneath the surface of the Earth can most simply be considered as consisting of a solid, self-supporting porous and permeable framework (or matrix), the porosity of which is filled by fluids. Even fine-grained rocks generally have some porosity and permeability and the fluids within them are commonly connected. The pressure in the rock matrix is determined by the weight of the rock above the point of interest (e.g. a coal seam) and the pressure on the fluids at that same point is commonly determined by the weight of the column of fluids above it. This explanation of fluid pressures in the subsurface is a simplification: there are many exceptions and coalbed methane in the UK is often underpressured with respect to the weight of the column of fluids above it (Creedy 1991).

Conventional gas, which exists in a free state in the pore spaces of a reservoir rock, is produced simply by opening the wells drilled into it. The pressure difference between the surface and the reservoir causes the gas to flow freely to the surface. By contrast, coalbed methane has to be desorbed from its adsorption sites within a coal seam. This is accomplished by pumping the well: any water in the coal seam is pumped out, lowering the pressure within the seam. This allows methane to desorb from the cleats and micropores and flow along the cleats into the production wells. Coal seams in coalbed methane wells are commonly fractured, to improve the connectivity between the coal and the production well(s).

Coalbed methane can be divided into three classes, depending on how it is recovered. These are:

CBM: Coalbed methane produced from unmined coal seams by the method described briefly above.

AMM: Abandoned mine methane that desorbs from coal seams into abandoned mine workings and is pumped directly from the workings to the surface.

CMM: Coal mine methane that is extracted by applying suction to cross-measures boreholes drilled in coal mines. This is undertaken principally to decrease the level of methane in mine air, allowing mining to proceed faster: the methane is a by-product that can either be used at the pit or sold.

2.2 DISTRIBUTION OF COAL-BEARING STRATA IN ONSHORE WALES

There are two main regions in Wales which are underlain by coal-bearing geological strata, much of which has the potential to produce methane. These are the South Wales Coalfield and the North Wales coalfields. The South Wales Coalfield extends into west Wales where it is known as the Pembrokeshire Coalfield. There are also other small coalfields in Anglesey and Pembrokeshire (Figure 2).

South Wales Coalfield

The South Wales Coalfield covers an area of approximately 2,000 km^2 measuring roughly 90 km from east to west and 27 km from north to south. It also extends offshore in Swansea Bay and Carmarthen Bay. The coalfield was extensively mined, principally over the last 200 years, with a peak production of approximately 57 million tons in 1913. The majority of the productive coals are found in the Lower and Middle Coal Measures formations. The coal is thickest in the western and south western parts of the coalfield, thinning to the east. The rank within the South Wales Coalfield ranges from high volatile bituminous coal in the south and east to anthracite in the north-west (Jones et al., 2004). The South Wales Coalfield contains a significant thickness of coal which meets the criteria to be a coalbed methane resource (Section 2.4) with the highest measured seam gas contents in the UK.

Pembrokeshire (Western South Wales)

The Pembrokeshire Coalfield has a surface area of around 130 km^2 and extends west from Amroth in Carmarthen Bay to Newgale in St Brides Bay. It comprises two small coalfields. The Little Haven to Amroth section is a continuation of the South Wales Coalfield. To the north is a smaller coalfield known as the Nolton-Newgale Coalfield. The coal seams are all of anthracite grade but their gas content is not known. In this region there are numerous thin coal seams which are heavily faulted and folded. Jones et al. (2004) considered that there is no realistic CBM potential in Pembrokeshire.

Anglesey

The Anglesey Coalfield covers an area of 25 km^2, underlying the wetlands of Malltraeth Marsh. Coal Measures are known to a depth of 358 m although the base of the succession has not been proved. The Anglesey Coalfield has at least 8 seams with only three being in excess of 0.4 m thick. Mining in Anglesey ceased in 1875 at a time when there was no routine recording of activities, hence there is no available data to indicate the rank or methane content of the seams. Jones et al. (2004) concluded that there is no realistic CBM potential in Anglesey.

North Wales

The North Wales coalfields crop out in a belt extending from Point of Ayr to Oswestry. They comprise the Flintshire, Denbighshire and Oswestry coalfields. The main coal seams occur within the Pennine Lower and Middle Coal Measures formations where the geological succession thickens towards the north and east. Rank also increases towards the north and east, where the coal measures extend underneath a cover of younger rocks. Coal measures are also found at depth in the Vale of Clwyd.

Together, the exposed coalfields of Flintshire, Denbighshire and Oswestry comprise an area of approximately 400 km^2. The Vale of Clwyd coalfield is estimated from boreholes to have an area approximately 200 km^2.

Rhuddlan 1 was a CBM exploration borehole in the Vale of Clwyd. It did not encounter commercial quantities of coal and on this basis, the Vale of Clwyd is considered of little interest for CBM (Jones et al., 2004). The Flintshire Coalfield is considered to be the most prospective for CBM in North Wales. This is due to evidence from Point of Ayr Colliery where significant gas flows were established from boreholes. The Flintshire Coalfield extends offshore where average values of 8.25m^3/tonne methane plus ethane were recorded in the North Dee prospect (Jones et al., 2004). The Oswestry Coalfield is unlikely to have seam gas content because it has few thick coal seams. Methane content has been measured in the deeper sections of the Denbighshire Coalfield and is considered to have a good resource potential (Jones et al., 2004).

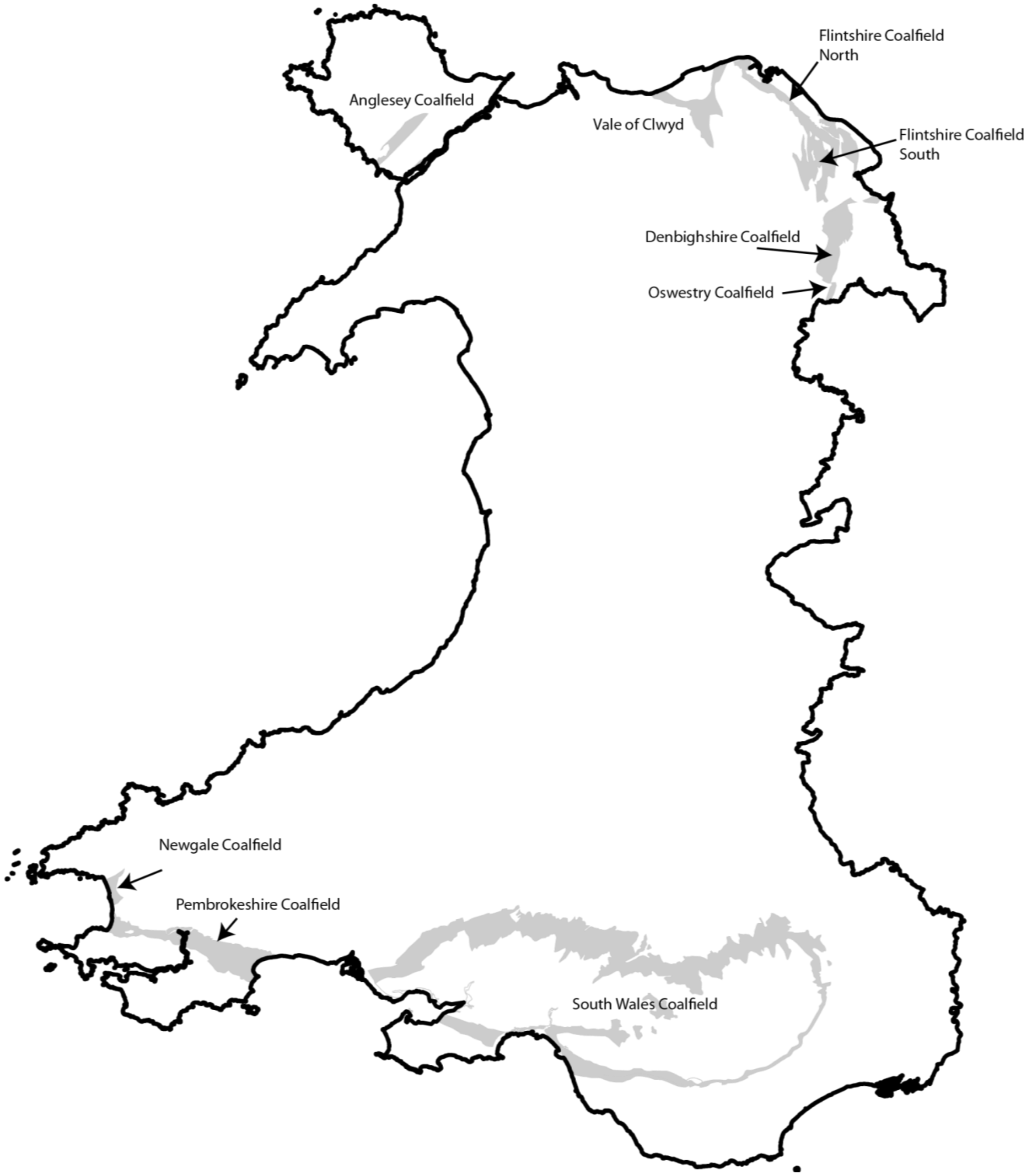


Figure 2 The surface outcrop of coalfields in Wales

2.3 DISTRIBUTION OF COAL-BEARING STRATA IN ADJACENT OFFSHORE AREAS

The Welsh coalfields extend offshore into the subsea (subsurface) from Swansea, Carmarthen and St Davids and into Liverpool Bay. (Figure 3 Offshore coal).

In North Wales, the offshore Coal Measures are mainly buried beneath a thick cover of younger Permo-Triassic rocks. However, they also outcrop at the sea bed, or beneath a thin cover of unconsolidated Quaternary sediments, adjacent to the Dee Estuary and offshore from Colwyn Bay. The Anglesey Coalfield also extends offshore, adjacent to the Llŷn Peninsula. The subsea (subsurface) extent has been interpreted from the results of borehole investigation and seismic reflection surveys, collected during extensive oil and gas exploration in the adjacent East Irish Sea Basin (Jackson et al., 1995).

The offshore areas of south and west Wales have not been the subject of widespread investigation by the hydrocarbons industry, and as such are less well characterised. The extent of Coal Measures illustrated in Figure 3 represents a very speculative understanding of the extent of the Coal Measures which may exist below a cover of younger rocks (e.g. British Geological Survey, 1999; Knight et al., 1996).

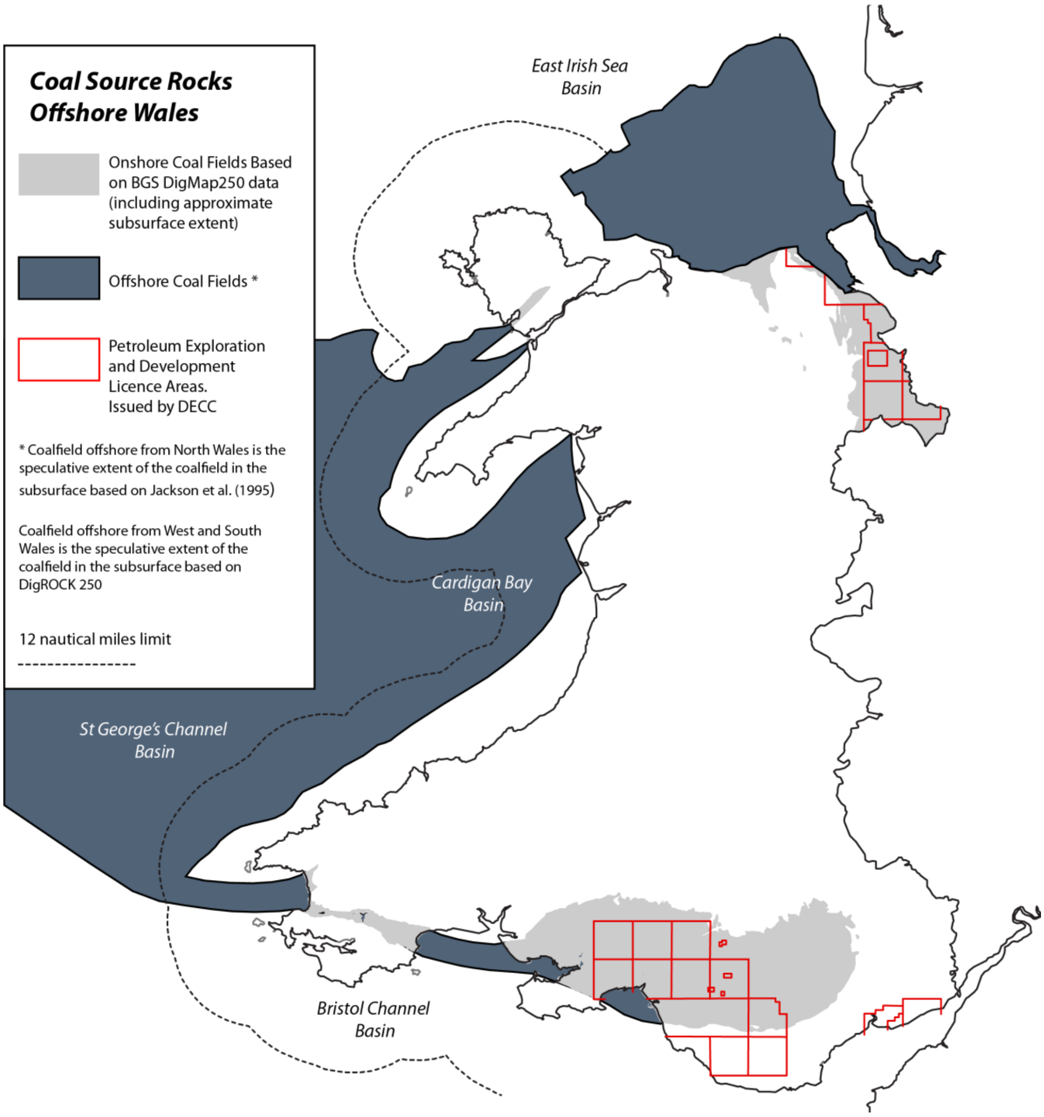


Figure 3 Offshore coal basins

2.4 COAL METHANE TECHNOLOGIES

The methane within coal can be extracted utilising a number of different technologies. This section contains a description of each of these techniques, a historical perspective on their application in the UK and resource estimates for Wales where known.

Gas resource estimates involve complex terminology and units of measure, often unique to the oil and gas industry. Appendix 1 provides a summary of the main concepts and explanation of terms used in this report. Under the Petroleum Act of 1998, the rights to all the UK's petroleum resources are vested in the crown. DECC grants licences which confer exclusive rights to search for and extract petroleum for limited periods. The licences are known as Petroleum Exploration Development Licences (PEDL). Underground coal gasification requires a licence under the Coal Industry Act of 1994 which is issued by the Coal Authority.

The South Wales Coalfield and the Flintshire Coalfield of North Wales are considered by Jones et al. (2004) to be the best prospects for methane from coal seams in Wales. This includes AMM where mine workings are not yet flooded. UCG potential appears to have most potential in parts of the South Wales Coalfield, and where it extends offshore and in the deeper parts of the Denbighshire and Flintshire Coalfields and their extensions offshore (Jones et al., 2004). CMM potential is absent at present because a lack of active deep coalmines.

Coal Bed Methane (CBM & VCBM)

The terms coal bed methane (CBM) and virgin coal bed methane (VCBM), both refer to the gas naturally occurring within un-mined coal seams.

Extraction Methods

Methane is recovered from un-mined coal seams via vertical or directionally drilled wells, drilled from the surface to meet the target coal seams. Directional drilling can be used to de-gas coal seams which have comparatively high porosity. Directional drilling ensures that as much of the borehole as possible intersects the fractures in the coal seam through which methane can flow. This is particularly effective, in the short term, if the borehole is drilled perpendicular the dominant cleat direction (Face cleat - See 2.1) although this effect diminishes with time (Davidson et al., 1995).

Most coal seams contain at least a little water (in the cleat and other fractures). The water can be extracted and as the pressure within the formation decreases, gas is able to desorb from the coal matrix and gas production increases (Jenkins et al., 2008). The process of extracting water from the coal seam is known as dewatering and can result in the production of significant quantities of (sometimes saline) water which needs to be managed (Section 4.1).

In commercial coalbed methane projects, vertical wells are often used to extract methane from shallow seams (150 to 1,000 m deep), where high permeability and low pressure means that flow enhancement techniques are not required. Directional drilling and hydraulic or nitrogen based fracture techniques can be used to enhance recovery of methane.

History of Exploration in the UK

To date, there has only been limited exploration for CBM in the UK. However, there are two pilot sites in the UK currently producing CBM. These are at Airth in Scotland, operated by Dart Energy Ltd, and Doe Green in Cheshire, operated by IGas. The first CBM borehole in the UK was drilled in 1992 at Sealand in Cheshire by Evergreen Resources. There has also been exploratory drilling in the Carlisle Basin, Cheshire Basin, East Midlands and South Wales coalfields.

There has been interest in producing methane from conventional and unconventional sources at Point of Ayr in Flintshire where IGas currently operates PEDL 107 and offshore licences, 110/23, 110/18a and 110/19a. CBM is of limited potential in this PEDL, although the offshore blocks are considered more prospective (IGas, 2009).

Resource Estimates in Wales

There are a number of studies focusing on CBM resource estimates for coalfield areas in Wales. Comprehensive regional estimates were produced by BGS on behalf of the DTI (Jones et al., 2004; Table 3; Figure 4). Other estimates have been produced by operators and typically these attempt to quantify the CBM resources for a specific licence area, rather than a whole geological basin. These estimates may be made by the operating companies or by independent third parties, and often the data is not available in the public domain for verification. Figures are quoted directly from the reference material in the units presented by the operators.

Jones et al. (2004) defined the presence of a CBM resource as being present below 100m of the top of the Coal Measures sequence of rocks. The presence of a resource was not taken to imply the presence of sufficient permeability within the coal seams or that other geological factors are favourable for establishing a reserve. In order to estimate the gas volumes within the coal Jones et al. (2004) list the factors which they considered reasonable indicators of the presence of methane. These include:

- limiting the estimate to coal seams which are greater than 0.4 m thickness.
- Only including coal seams which are at depths of between 200 and 1,200 m.
- Including coal seams with a gas content of greater than 1 m^3/tonne.
- Including only the areas of coal with less than 100 m vertical separation from principal aquifers and geological unconformities*.
- Excluding coal seams which have 500 m or less horizontal separation from underground coal workings*.
  *These areas were not considered because of the risk of contamination in the case of aquifers, and proximity to unconformities may provide pathways for pollution.
- Only including areas within 500m of underground workings, or seams which lie less than 150 m above or 40 m below previously worked seams are not considered as they may have already degassed into the workings during mining operations.

Jones et al determined that there is a significant total thickness of coal meeting these criteria, resulting in an excellent resource base. However, in South Wales, the extent of previous underground workings is likely to be a limiting factor. Although the resource estimate for the North Wales Coalfield is lower, Jones et al. (2004) remarked that areas of un-mined coal are still present. Jones et al. (2004) noted that the South Wales Coalfield has the highest seam methane contents in the UK, reaching over 22m^3/ t in the anthracite belt in the north-west of the coalfield. Minimum values in the south-east are generally about 5.5m^3/ t of coal.

Area	Area (km^2)	Average Methane content (m^3/t)	Resource ($10^6 m^3$)	Resource density (m^3/ m^2)
South Wales 1	58.5	20	27247	466
South Wales 2	16.8	22.5	6666	397
South Wales 3	127.3	17.5	35007	275
South Wales 4	244	8.5	55803	229
South Wales 5	342.4	14.5	64546	189
South Wales 6	290.1	11.5	54706	189
South Wales 7	306.6	5.5	45753	149
South Wales 8	451.5	Unknown	Unknown	Unknown
North Wales 1	60.5	8	15655	259
North Wales 2*	Unknown	8	Unknown	Unknown
North Wales 3*	Unknown	6	Unknown	187
North Wales 4*	Unknown	8	Unknown	166
North Wales 5	132.5	7.1	Unknown	30
Anglesey		Unknown	Unknown	Unknown
Pembrokeshire		<10	Unknown	Unknown

Table 3 Methane resource values for Wales after Jones., et al (2004)

*** Areas extend beyond Wales.**

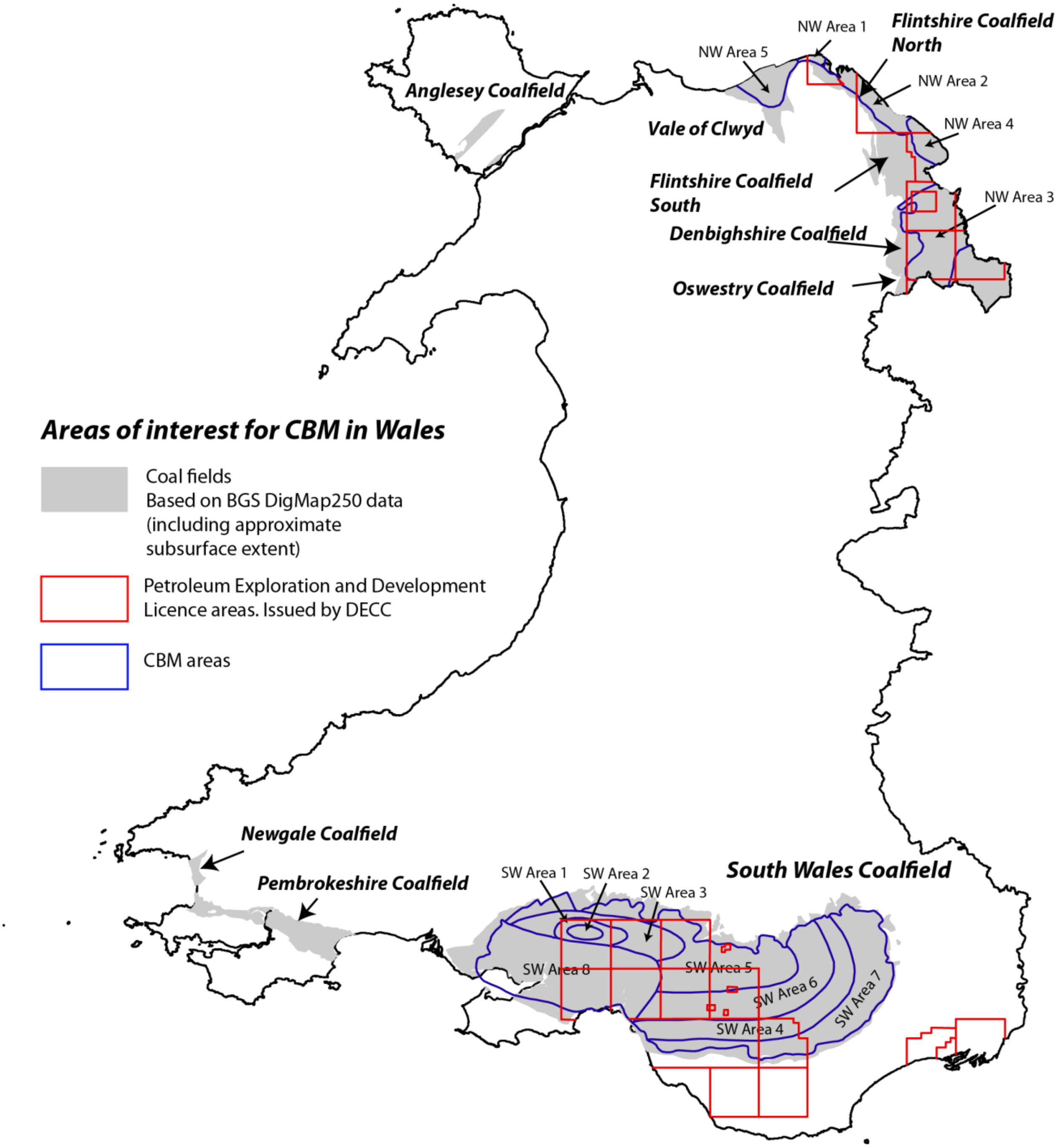


Figure 4 Areas of interest for CBM based on Jones et al. (2004)

Of the available private sector estimates, IGas in their Annual Report of 2009 reported resource estimates from their licence areas around the Point of Ayr (Table 4). They concluded that the Coal Measures in their onshore licence area (PEDL 107) have limited potential for CBM because the seams have already been extensively mined. In 2009, IGas also held offshore licences in SPPL 148, which includes parts of blocks 110-18, 110/19 and 110/23 and have proven Coal Measures in boreholes from block 110/19.

GIIP (Billions of standard cubic feet -bscf)				
Name	**Licence**	**P90**	**P50**	**P10**
Point of Ayr Offshore A	PEDL 110/19 & 107	304	491	941
Point of Ayr Offshore B	PEDL 110/18 & 23	791	1170	2302
Total		**1095**	**1661**	**3243**

Table 4 CBM resource estimates for Point of Ayr (Sami et al., 2011)

Eden Energy Ltd with UK Onshore Gas Ltd. commissioned studies of their CBM assets from RISC Operations Pty. Ltd. for their assets in South Wales. RISC reported Gross Contingent Resource (Appendix 1) on the 10 licences (Including the following PEDLs in which Eden Energy Ltd has a part or complete interest in: 212,148, 214, 215, 149, 218, 221, 223, 100 & 220), an area of 247 square kilometres. They estimated a 1C to 3C range of 687-1363 bcf with a 2C estimate of 980 bcf of gas. RISC reported that they used data from wells and coal mining operations to make their estimates and that their areas were estimated after adjusting for urban, mined out and restricted access areas. The coal depths range from 600m to 1200m with total coal thicknesses averaging 20m. Their review has also shown average gas contents of 11.9m^3/t across the licence areas which increases to over 20m^3/t towards the north (Eden Energy Ltd, 2012).

Dart Energy Ltd has licences in North and South Wales. Their South Wales assets include PEDL 211 and EXL 284 in which they have 100% working interests. Their Swansea PEDL has an area of 134 km^2 with CBM estimated resources of 614 (best estimate) to 1,121 (highest estimate) bcf OGIP. The Dart Energy Ltd web pages report contingent 3C resources are estimated at 750BCF and 2P as 320 bcf (Dart Gas, date unknown)(Appendix 1).

In North Wales, Dart Energy Ltds licence area extends into England covering an area of 717 km^2. Estimates reported on the Dart Energy Ltds web pages for OGIP are 3,197 (best estimate) to 5,041 (high estimate) with 3C contingent of 3,195 and 2C contingent of 1,683 bcf (Dart Gas b. Date unknown).

Geological Constraints

There are a number of geological factors that contribute to uncertainty in CBM resource assessments. These include heavy faulting; low seam permeability; variable or low gas content and unpredictable gas pressure and water saturations at surface (see section 2.5 for a discussion of geological risks). Of these, low seam permeability is generally considered to be main factor influencing gas production in the UK (Jones et al., 2004).

Abandoned Mine Methane (AMM)

Abandoned mine methane consists of mainly methane gas which has become trapped in abandoned coal mines. The term can also be applied to methane that can be released from coal seams into the strata surrounding the mined seam by applying suction to mine workings (Creedy et al., 2001).

Extraction methods

AMM can be produced from unflooded abandoned deep coal mines where coal extraction has lead to the collapse of the underlying and overlying strata into the space from which the coal has been extracted. The reduction of stress on the surrounding strata forms fractures and increases the permeability of coal, allowing Methane to accumulate in the abandoned mine workings. The zone of reduced stress is typically estimated to be 150-200 m above and 40-70 m below the mined seam (Creedy et al., 2001). AMM is exploited by drilling from the surface into the worked out and collapsed areas of a mine (Thomas, 2002) or by tapping into pre-existing ventilation shafts (World Coal Association, 2013).

History of Exploration

There is a long history of AMM production in Belgium, France, Germany and in the UK. AMM exploitation in the UK is known as far back as 1954 when the National Coal Board extracted methane for electricity generation at Old Boston Colliery in Lancashire (Jones et al., 2004). Some examples of AMM exploitation include: Green Gas Power Ltd. from Silverdale Colliery, in Staffordshire; Alkane Energy Plc. at 5 sites in England; Green Park Energy operates one site and are considering more; and Warwick Energy drains methane from the abandoned Bentinck Colliery, in Nottinghamshire (The Coal Authority, 2013).

In South Wales, Alkane Energy UK Ltd. applied for planning consent to extract mine gas from the abandoned mine workings associated with Garw/Ffaldau collieries in Pontycymmer. This was based on an exploratory borehole which was drilled in 2002 to a depth of 128m below ground level. The borehole encountered unflooded mine workings which contained gas under pressure. The plan proposed collecting gas at the surface and utilising a generating station to produce 1.6 mega watts of electrical power to feed into the Western Power distribution grid. The recommendation was to approve the application in 2011 (Bridgend County Council, 2011).

In 2005, it was reported that in North Wales, gas has been extracted from Llay Main Colliery abandoned workings since 2004 (BBC 2005). The project was initially set up by Evergreen Resources and is now operated by BioGas Technology Ltd.

Resource Estimates

Resource assessments for AMM potential require the consideration of the volume of voids in former mine workings available for gas accumulation, the volume of surrounding, de-stressed coal available to release gas, estimates of seam gas content (>1m^3/tonne is significant) and mine water recovery. Shallow workings are generally excluded as they may be connected to the surface, allowing air ingress during methane extraction.

The required information is provided by an understanding of the sub-surface geology provided from detailed seam plans, shaft sections and borehole records, and by a good understanding of the state and rate of minewater recovery. In Wales, these datasets are generally incomplete, hence Jones et al. (2004) did not produce resource assessments for AMM and no resource areas were defined.

Geological Constraints

The main geological factors influencing quantity and quality of gas, rate of groundwater recovery effectively reducing the accessible volume of mine workings and inadequate sealing of mine entrances allowing air ingress and gas to escape.

Coal Mine Methane (CMM)

Coal mine methane refers to the methane that occurs in coal and its associated strata, which is produced during mining operations.

During mining, the reduction of stress on the surrounding strata causes fractures and increases the permeability of coal, allowing methane (traditionally known as firedamp in the mining industry) to flow into the mine workings. The zone of reduced stress is estimated to be typically 150-200 m above and 40-70 m below the mined seam (Creedy et al., 2001). Levels of methane in mine workings have to be kept below safe levels to allow mining to proceed.

Extraction Techniques

CMM flowing into mine workings is typically managed by a combination of ventilation and drilling horizontal or inclined cross-measures boreholes into coal seams and surrounding strata ahead of mining operations (Thomas, 2002). Suction is applied to the boreholes and the methane is transported out of the mine via pipework where it can be utilised.

History of Exploration

Methane produced during coal mining is considered a safety hazard. Historically this has been controlled by mine ventilation, but more recently methane has been captured and utilised (Jones et al., 2004).

One example of CMM utilisation in Wales, reported on the Coal Authority website (Department of Energy and Climate Change (2013d), is that of Tower Colliery in South Wales, which, as part of its underground mining operations, drained methane from its active workings. Hyder Consulting, in partnership with Tower Colliery, installed 6 x 1.5 MW generators to utilise the gas. The electricity generated was fed into the National Grid.

Resource Estimates

A CMM resource area is defined as the mining area licence around a working mine with a methane drainage scheme. At the end of 2012, there was only one deep mine listed in Wales. This is the Unity Mine (Department of Energy and Climate Change, 2013a) which went into administration in October 2013 (Wales Online, 2013); hence there are no CMM resource areas defined in Wales at present. However, Aberpergwm Colliery is undergoing redevelopment (Department of Energy and Climate Change, 2013a) and a resource may become viable in the future.

Geological Constraints

The main geological constraints on estimating CMM resources include premature mine closure mines closing prematurely which may in itself be caused by geological factors, and variable supply and quantity of methane present within the seam being worked.

Underground Coal Gasification (UCG)

Underground coal gasification is a process by which air, oxygen and steam are injected into coal seams at depth in order to partially combust the coal. The injectant reacts with the coal and produces heat, hydrogen, carbon monoxide and methane and in some seams, sulphur gases. The mixture of gases which are produced, known as syngas, are similar to 'town gas' which was produced from coal before the introduction of natural gas from the North Sea.

Extraction Techniques

UCG production is normally achieved by utilising at least two boreholes. The injectant is introduced through one borehole and reacts with the coal which produces heat and Syngas which are collected via a separate production well or wells (Jones et al., 2004).

History of Exploration

The earliest records of UCG date back to 1868 when Sir William Siemens suggested gasifying coal in situ to the British Chemical Society. The first experiments were carried out in Russia in the 1930s. In the UK, the National Coal Board carried out shallow tests of UCG in Derbyshire and Staffordshire in the 1950s and, around the same time, trials were conducted in Texas in the USA (Klimenko, 2009). The process was also used in Germany during World War II. Other recent examples include a pilot UCG operation in Australia, which produces diesel by utilising the Fisher-Tropsch process where hydrogen and carbon monoxide, derived from coal or Methane are converted into liquid fuel (United States Department of Energy, 2011). SASOL Ltd. are also exploring UCG technologies in South Africa (SASOL, 2014). More recent tests have also been conducted in the El Tremedal experiment in Spain (UCG Association, 2011).

Resource Estimates

In their regional review, Jones et al. (2004) considered a conservative minimum depth of 600m for UCG. Although there are examples of shallower schemes, those at a greater depth were considered to have less potential for aquifer contamination, ground subsidence or gas escape. A maximum depth of consideration was 1,200 m which was the normal limit for mining in the UK. A minimum coal seam thickness of 2 m was recommended for economic reasons and because UCG in thinner seams was thought to be less effective. The study also incorporated a buffer of 500m around coal mining licence areas intended to protect those resources and operations and a separation of 100 m from major aquifers.

Applying these criteria, Jones et al. (2004) identified areas of “good and unverifiable” resource for UCG. “Good” conditions are present in the western part of the South Wales Coalfield where unmined coals are preserved at greater depth and also in north-east Wales (Figure 5).

Areas of coal measures which may have UCG potential also occur where the coalfields extend offshore (Figure 3). In South Wales this could include Swansea Bay and Carmarthen Bay. In South Wales, Clean Coal Ltd. held offshore conditional UCG licences in the UK, including one in Swansea Bay. Although Clean Coal Ltd do not report gas resource estimates, they do reported via their web pages an estimated minimum coal reserve of 206 mt (metric tonnes) assuming an average seam thickness of 2 m and 515 mt assuming an average seam thickness of 4 m providing a minimum amount of coal recoverable of 124 mt and a maximum of 309 mt. Clean Coal Ltd. also suggested that this resource could produce 0.5GW energy production for 20-30 years. Cluff Natural Resources presently have conditional licences for UCG in the Loughor Estuary in Carmarthenshire and in the Dee Estuary in North Wales (Cluff Natural Resources, 2014).

Geological Constraints

The main geological constraints associated with UCG relate to poor sealing of the combustion cavity in the presence of faults and permeable coal or host strata. These could promote aquifer contamination or quenching of the reaction, poor combustion or fugitive emissions of potentially harmful combustion products.

The process of underground coal gasification reduces coal to ash in situ, resulting in creation of void space underground, which can lead to roof collapse. The collapse of cavities can also result in possible contamination effects to aquifers and surface subsidence is possible. The extent of surface effects is likely to be of minimal significance unless the depth of operation is shallow (Whittaker and Reddish, 1989). Overburden collapse can be mitigated by injection of support material and regional subsidence can be monitored using ground surveying and remote sensing techniques.

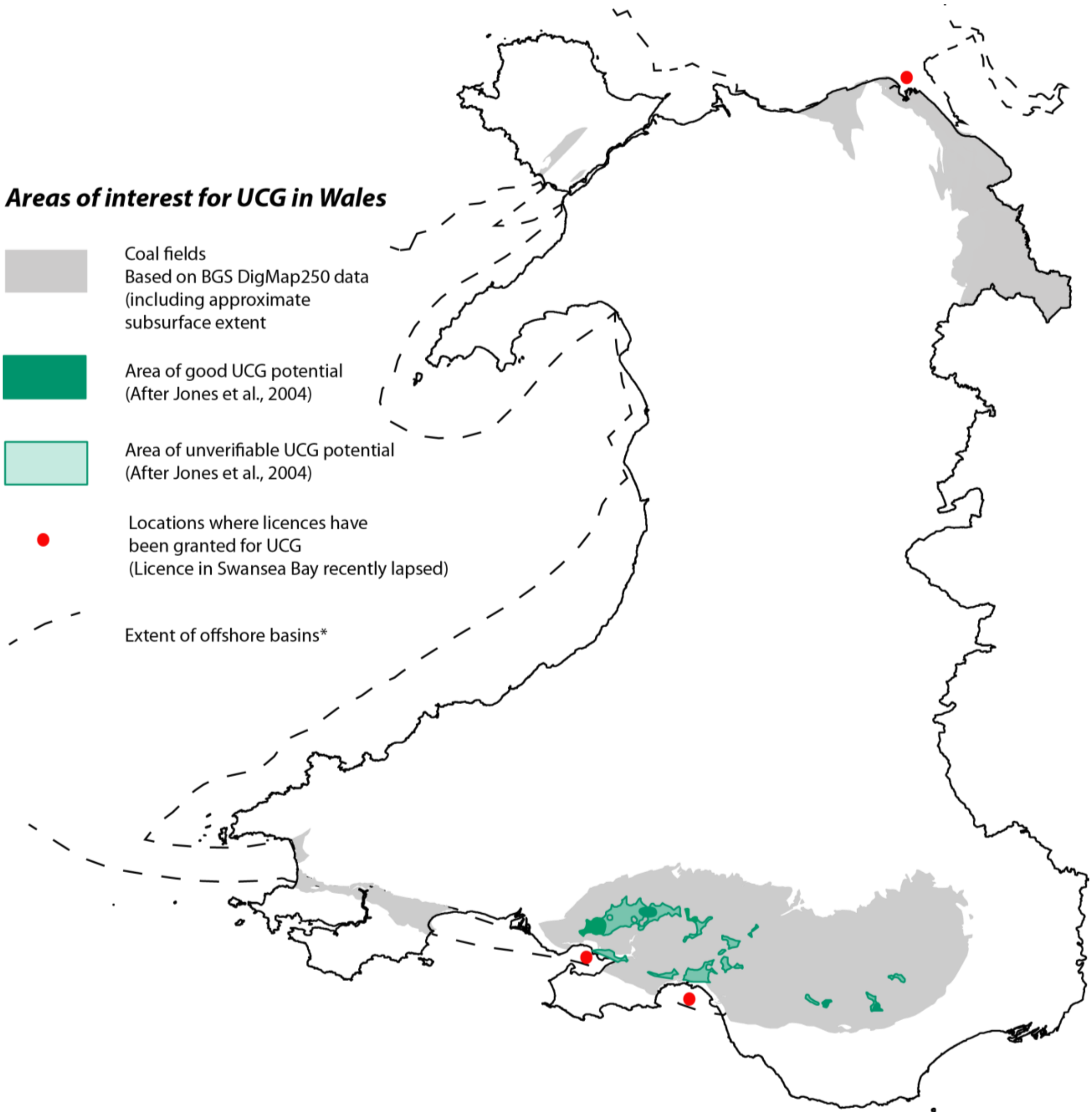


Figure 5 Areas of interest for UCG after Jones, et al. (2004)

'* See Figure 3 Offshore coal

2.5 CARBON CAPTURE AND STORAGE (CCS)

Carbon dioxide (CO_2) is a naturally occurring gas at normal temperatures and pressures in the Earth's atmosphere. One of the outcomes of burning carbon-based fuels is the increased concentration of CO_2 in the atmosphere which can contribute to global warming and ocean acidification. A mechanism by which CO_2 emissions could be reduced is to capture CO_2 from the industrial processes where it is produced (for example fossil fuel power plants), and transport and store CO_2 in underground, geological formations rather than releasing it to the atmosphere. This process for storing CO_2 underground is known as carbon capture and storage. Injection of CO_2 via wells into depleted oil and gas fields or saline aquifers or un-minable coal seams all have the potential for its long term storage. There is also research into the possibility of sequestering CO_2 into shales to enhance methane recovery but this technology is considered to be too new to be a realistic consideration at present (Lee et al., 2011; Jikich et al., 2003).

Of most relevance to this report is the potential to utilise un-minable coal seams to store CO_2 in the South Wales and the North Wales Coalfields and their offshore extensions. Coal is microporous and often highly fractured, providing space for gas molecules to diffuse and be adsorbed. Coal has a higher affinity to adsorb CO_2 than methane, so injection of CO_2 can drive out methane present within a coal seam and thus provide potential for enhanced methane recovery (also known as 'enhanced gas recovery', EGR). Wolf et al. (1999) suggests that coal can adsorb twice the volume of CO_2 as methane and lower rank coals can adsorb 6 to 8 times as much CO_2 as methane (Gluskoter et al., 2002). Kaniów is a demonstration site in Poland. The coals are of the same age as those found in Wales, although of a different grade and depth. At Kaniów, they found that 91% of the injected CO_2 was adsorbed by the coal, with the methane produced containing some 40-60% CO_2 (Benedictus et al 2008). Injected CO_2 that is not absorbed by the coal can migrate upwards through overlying, permeable rock formations, because it is bouyant in comparison to the fluids which normally fill the pore space those in geological formations. The coal seams at Kaniów are overlain by younger, clay-rich, Triassic aged formations that form an impermeable seal, preventing any CO_2 that escapes the coal seams from reaching the surface.

CCS in coals seams is an immature technology and the method has yet to be proven to enhance commercial coalbed methane production.

2.6 MAIN GEOLOGICAL FACTORS INFLUENCING COAL METHANE RESOURCES IN WALES.

The main geological factors that can have an impact on the estimation and exploitation of coal gas resources have been described above. There are also areas of uncertainty associated with defining and mapping resources which have an effect on coal gas resource estimates.

Data Availability

Confidence in the understanding of the geology in the subsurface is at its highest at, or close to, a data point such as a borehole or seismic reflection line. Therefore, the more data present in an area of interest, the more confidence can be applied to the interpretation. Because resource and reserves calculations rely on understanding volumes and distribution of target geological strata, confidence in them increases in areas of higher data density, in particular, in areas with a high density of boreholes or shafts which intersect the strata of interest (Jones et al., 2004).

Data reliability

Whilst borehole data is often the best source of subsurface information, the accuracy and the dependability of the descriptions can be difficult to assess. Problems typically arise from drilling-related issues such as poor recovery, poor telemetry and the presence of faults which can make an assessment of the geological succession difficult. Descriptions of older boreholes can also have inaccuracies with depth recording and poor descriptions of recovered material.

Faults

It is important to understand the presence or absence of geological faults in an area of interest as well as their properties. Geological faults can have major impacts on the development of Coal Methane projects. Geological faults can result in the vertical and/or lateral displacement of coal seams that are of interest for methane and the targets for drilling. They can also provide conduits for fluid and gas movements which can affect the resource remaining in the ground or potential pathways for pollutants associated with drilling. Some geological faults can also be barriers to fluid or gas flow, effectively reducing overall permeability.

Aquifers

Issues associated with aquifers close to UCG resources are discussed in Section 4.1. In Wales, the principal aquifers do not lie within the Coal Measures geological units. However, secondary aquifers within the Coal Measures, for example sandstone rich units, will need to be taken into account whilst undertaking coal methane projects. Ensuring separation from groundwater aquifers ensures that they are protected from potential contamination by drilling operations, fluid injection or gas production.

3 Unconventional gas from shale

3.1 WHAT IS SHALE GAS?

Shale gas comprises mainly methane that is recovered from organic rich rocks known as shales, but are more precisely termed mudstones and siltstones.

Shales are sedimentary rocks which mainly comprise fine grained (clay and silt sized) particles deposited in marine and to a lesser extent, lacustrine environments. Shale may contain organic matter, which is typically derived from higher land plants, aquatic plants, bacteria and animal remains deposited by settling of pelagic material through the water column. Low oxygen conditions on the sea or lake bed favours the preservation of the organic matter. Such conditions often relate to broader, often global, geological processes such as periods of marine transgression, or development of restricted sedimentary basins in which stratified water columns with anoxic benthic conditions develop (Challands et al., 2009; Smith, 1987).

There are two main processes for methane generation in shales. Gas can be generated by bacterial action as organic matter degrades. This is known as biogenic methane and the gas formed may be released to the ocean and atmosphere prior to burial, but can also continue to be produced after burial.

The second process of methane generation is by thermal maturation of primary organic matter. This occurs when the organic rich muds and silts become buried over geological time; burial is associated with increasing temperature in the absence of oxygen, a process that causes the break-down of complex organic matter to yield simpler hydrocarbons which include methane.

Methane is held in three distinct scenarios within shales: preserved as free gas inside the microporous structure and in natural fractures within the rock; dissolved in pore fluids and adsorbed onto the organic matter and clay minerals contained within the shales (Zhang et al., 2012).

Clues as to likely prospective areas can come from the conventional hydrocarbon industry which is well developed in the North Sea and nearby Irish Sea. A conventional hydrocarbon system can be defined as one where commercial quantities of hydrocarbons are typically gained from wells with no additional stimulation. Unconventional hydrocarbons can be defined as those where, upon drilling, commercial rates of hydrocarbons can only be gained with further intervention such as hydraulic fracturing. Conventional systems normally consist of source rocks, reservoir rocks and a cap rocks. As the names suggest, the reservoir rocks host the hydrocarbons which are prevented from rising to the earth’s surface by an impermeable cap rock. The source rocks (including carbonaceous shales) are where hydrocarbon generation occurs and so have been the focus for study in the conventional hydrocarbon industry. With shale hydrocarbon systems, methane is generated, stored and trapped within the host shales, which have low porosities and extremely low permeabilities.

3.2 GEOLOGICAL INDICATORS OF A SHALE GAS RESOURCE

Classification of shale gas resources is difficult because of a large degree of variability among commercially exploited shale gas plays elsewhere in the world. This presents difficulties for assessing potential resources in Wales, where there is little exploration data. However, the best shale gas resources discovered to date share some common geological characteristics which include favourable type of organic matter, maturity and permeability, sufficient gas-in-place, predictable stress field and structurally simple, regionally extensive and continuous strata (Jarvie, 2012; Appendix 3).

Gas resource estimates involve complex terminology and units of measure, often unique to the oil and gas industry. Appendix 12 provides a summary of the main concepts and explanation of terms used in this report.

3.3 SHALE GAS POTENTIAL IN WALES

In Wales, there are a number of shale horizons which may have potential for shale gas and these are described in the following sections. However, to date there has been no attempt to provide a resource assessment for Wales as a whole. This paucity of information reflects a lack of legacy data from conventional hydrocarbon exploration in the region. Further information would be provided by the results of exploration and research programmes. The Department of Energy and Climate Change (2010a) produced a report which identified the shale formations in the UK which are potentially a shale gas resource.

There are a number of geological horizons that are of interest in Wales (Department of Energy and Climate Change, 2010a). The middle Carboniferous shales are considered the best prospect and are consequently attracting the most interest and investment from exploration companies. This is because they are rich in organic content and thought to be analogous to the commercially exploited Barnett Shale of the USA, and the Bowland-Hodder unit of northern England. In Wales, the subsurface structure of the middle Carboniferous shales is comparatively well understood.

Other geological units in Wales potentially contain organic matter, but are much less-well understood due to a lack of data and are considered less attractive exploration targets. These rocks include the early Carboniferous shales and selected units of Lower Palaeozoic shales. Carbonaceous mudstones also occur at intervals throughout the Lower Palaeozoic succession in Wales making them of interest for exploration. The Lower Palaeozoic shales include Ordovician aged shales. The Utica Shales of the USA are prospective for shale gas and are also Ordovician in age. However, a much better understanding of their geochemistry, structure and subsurface distribution of the early Carboniferous shales and the Lower Palaeozoic shales is required to provide the confidence required for commercial exploration.

Middle Carboniferous Shales

Shales from the middle part of the Carboniferous sequence are the source rocks for hydrocarbon fields in the East Midlands, Formby and offshore in the East Irish Sea (Department of Energy and Climate Change, 2010a, Glennie, 1998). In North Wales, this geological succession includes the Bowland-Hodder unit (formerly Holywell Shales Formation) thought to be contiguous with strata in Liverpool Bay and Northern England where they are the target of the present shale gas exploration in Lancashire (Figure 7). Rocks of a similar age are found in South Wales which are the Bishopston Mudstone Formation (Figure 7). However, there is much less known about the organic content and character and mineralogy of this formation in comparison to its equivalent in North Wales. This association has attracted attention from exploration companies who have invested in resource estimates for their licence areas.

BGS undertook a study of the Bowland-Hodder shales which extends across the north of England and into a small area of North Wales (Andrews, 2013a). A further report was commissioned by Welsh Government to provide an estimation of that resource that may be found within Wales (Andrews, 2013b; Table 3). Only a small volume of this unit is considered prospective compared to the total distribution of the Bowland-Hodder unit. (Figure 6, Figure 7).

Upper P90	Upper P50	Upper P10	Lower P90	Lower P50	Lower P10	Total P90	Total P50	Total P10
0.1	0.2	0.4	6.2	10	17.4	6.4	10.3	17.8

Figures are expressed in trillion cubic feet (tcf)

Upper = Upper Bowland-Hodder unit

Lower = Lower Bowland-Hodder unit

Total = combined, total Bowland-Hodder unit

P10, P50, P90 probability of that amount being present.

Table 5 Resource estimates for Bowland Shale in Wales (Andrews, 2013b).

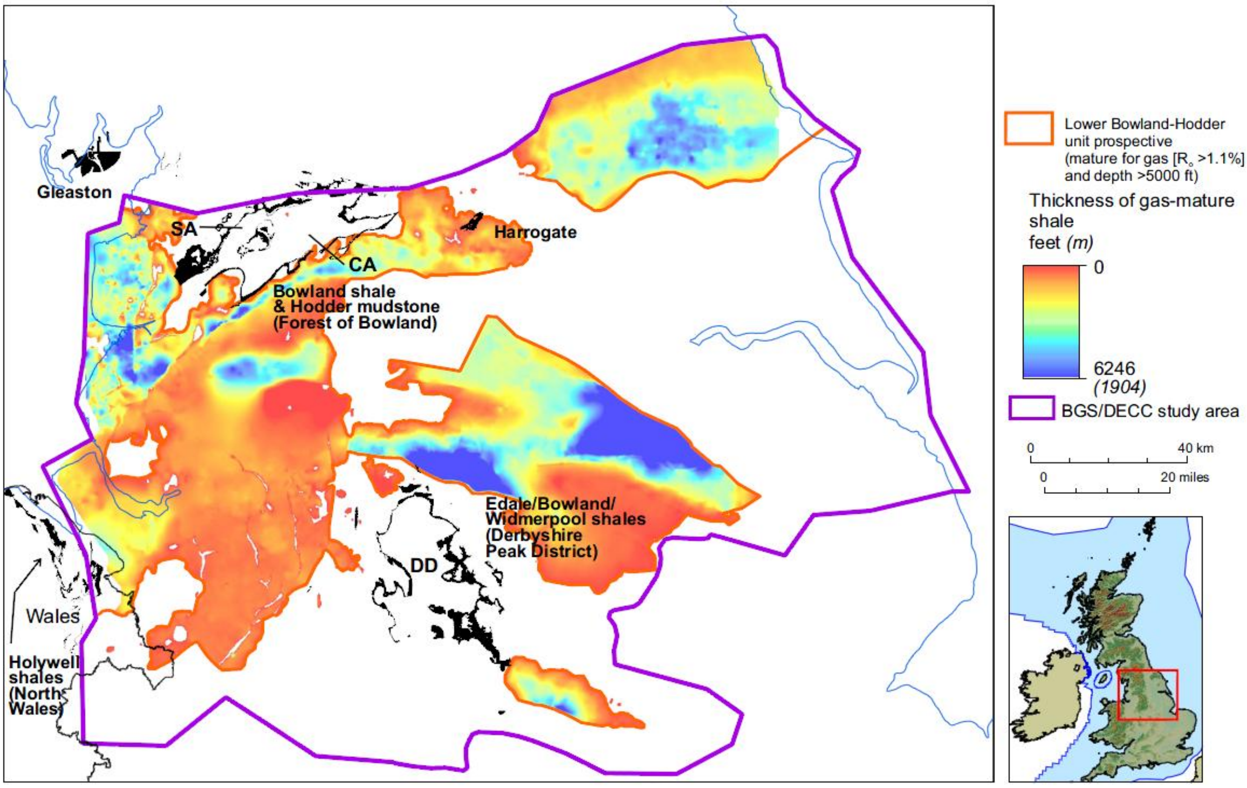


Figure 6 Thickness and distribution of lower Bowland-Hodder unit which are within the gas window and at greater than 1524m (5000ft) (Andrews, 2013a)

There are two other resource assessments available for North Wales. These are both produced by commercial operators for their individual licence areas. They both state that the shale gas potential they describe is from the middle Carboniferous Shales, although, the details, data and methodology used to calculate the assessments have not been released. Figures are quoted directly from the reference material in the units presented by the operators.

IGas Energy Plc. currently has onshore and offshore licences in North Wales continuing offshore to the north of Point of Ayr (Figure 3). They have completed a preliminary assessment for shale gas within the middle Carboniferous Shales and have reported that shales extend across their licence area (1,195km^2) and have an expected average thickness of approximately 250 m (IGas, 2009). They report that the shales are understood to be hydrocarbon bearing as they are locally demonstrated to be the source rock for hydrocarbons in the Liverpool Bay area and cite Total Organic Content (TOC) ranging from below 0.7% to over 5% with an average in the Bowland-Hodder unit (Holywell Shales) of around 2.1%.

Dart Energy Ltd. holds licences in north-east Wales that straddle the border between England and Wales. These are PEDL 147, 185, 186, 187, 188, 189 and EXL 203, which they state are prospective for shale gas. They estimate a total (Original Gas-in-place) OGIP prospective resource of 30,550 bcf (Billions cubic feet) across its Wrexham/Cheshire assets. However it is not known how this resource is divided between England and Wales (Dart Gas b, date unknown).

Middle Carboniferous shales occur in South Wales, underlying the South Wales Coalfield. Although these rocks are the same age as the Bowland-Hodder unit, there has been much less research on which to assess their prospectivity. RPS Group Plc. were commissioned to produce a resource assessment for UK Onshore Gas Ltd. and Eden Energy Ltd. for their 7 PEDL licences in South Wales, an area of 806 km^2. RPS based their estimate on the understanding that middle Carboniferous Shales underlie their licence area and presented an unrisked P90 Resource Volume Estimate 34.198 tcf (GIIP) and recoverable volume of 12.799 tcf of gas. These figures were based on reviewing analysis from available drill core, and modelling a number of chemical and physical properties across the relevant area (Eden Energy Ltd, 2012). In written Evidence submitted to the House of Commons Select Committee, Energy Generation in Wales: shale gas by UK Onshore Gas Ltd, they report slightly higher resource estimates of 49.8tcf GIIP and 18.3tcf recoverable volume of gas from the same area.

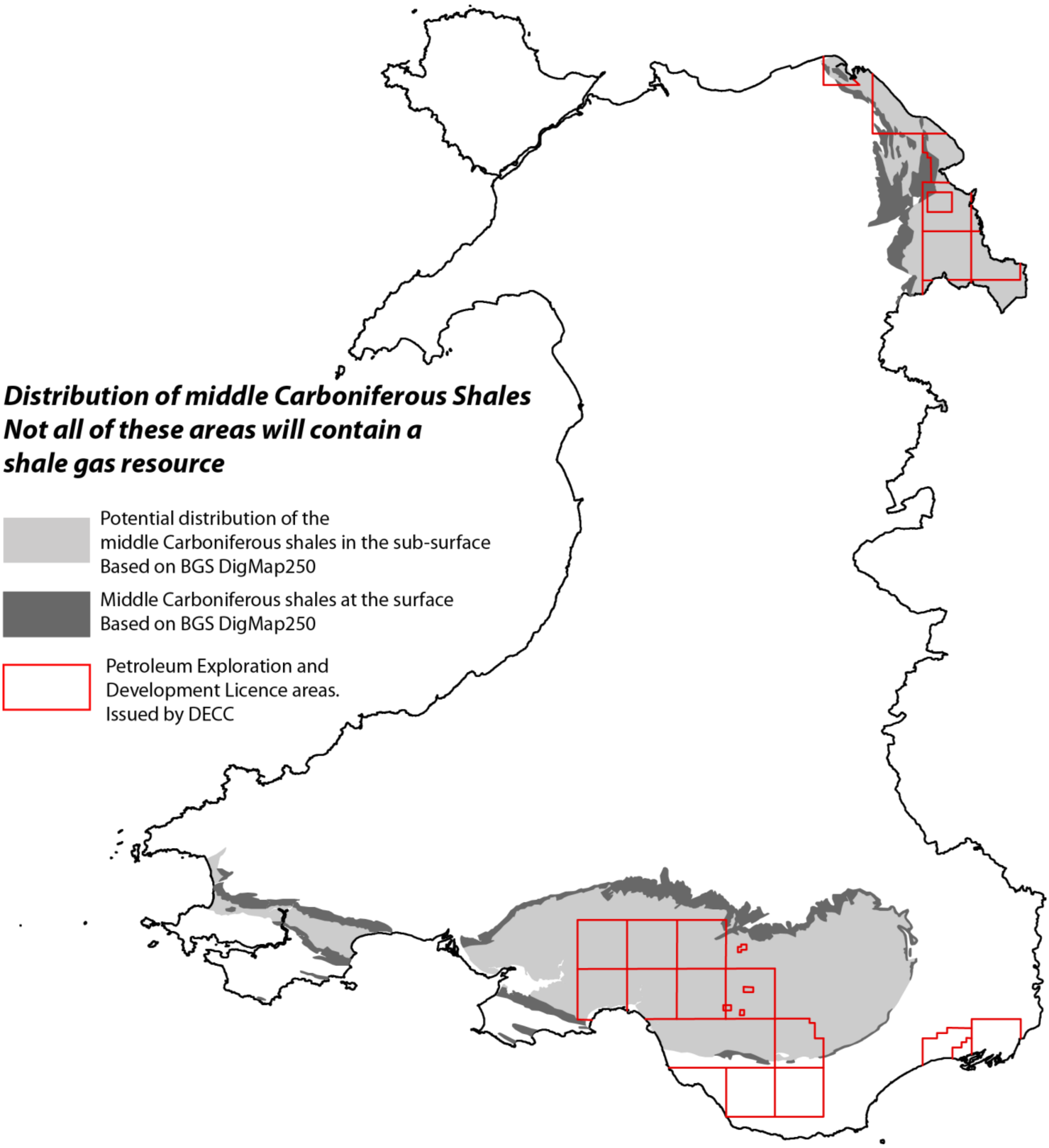


Figure 7 Distribution of middle Carboniferous shales

Early Carboniferous Shales

In South Wales, the early part of the Carboniferous succession comprises the Avon Group (formerly termed 'Lower Limestone Shales') and the younger, Oystermouth Formation. This Avon Group includes a number of formations, some of which contain units of carbonaceous mudstones. Vitrinite Reflectance values of over 3.5% are recorded from the Cannington Park Borehole (BGS Ref: ST23NW6) (south Bristol) for this group of rocks, although the primary information is not available (Department of Energy and Climate Change, 2010a). More scientific research on carbon type and quantity, maturity and mineralogy within these units is required to establish if this unit is prospective for shale gas, within Wales.

Also of interest is the Oystermouth Formation (Formally known as the Upper Limestone Shales) which comprises interbedded black, impure limestones and calcareous mudstones (Barclay, 2011). A borehole drilled in Maesteg showed that the Oystermouth Formation contains carbonaceous mudstones, interbedded with thick sandstones and underlain by limestone (Department of Energy and Climate Change, 2010a).

The early Carboniferous shales of Wales were deposited in a similar setting and are of a similar age to the shales of the Fort Worth Basin in the United States of America. Rocks of the Fort Worth Basin includes the Barnett Shale which is prospective for shale gas (Department of Energy and Climate Change, 2010a and Selley, 2005).

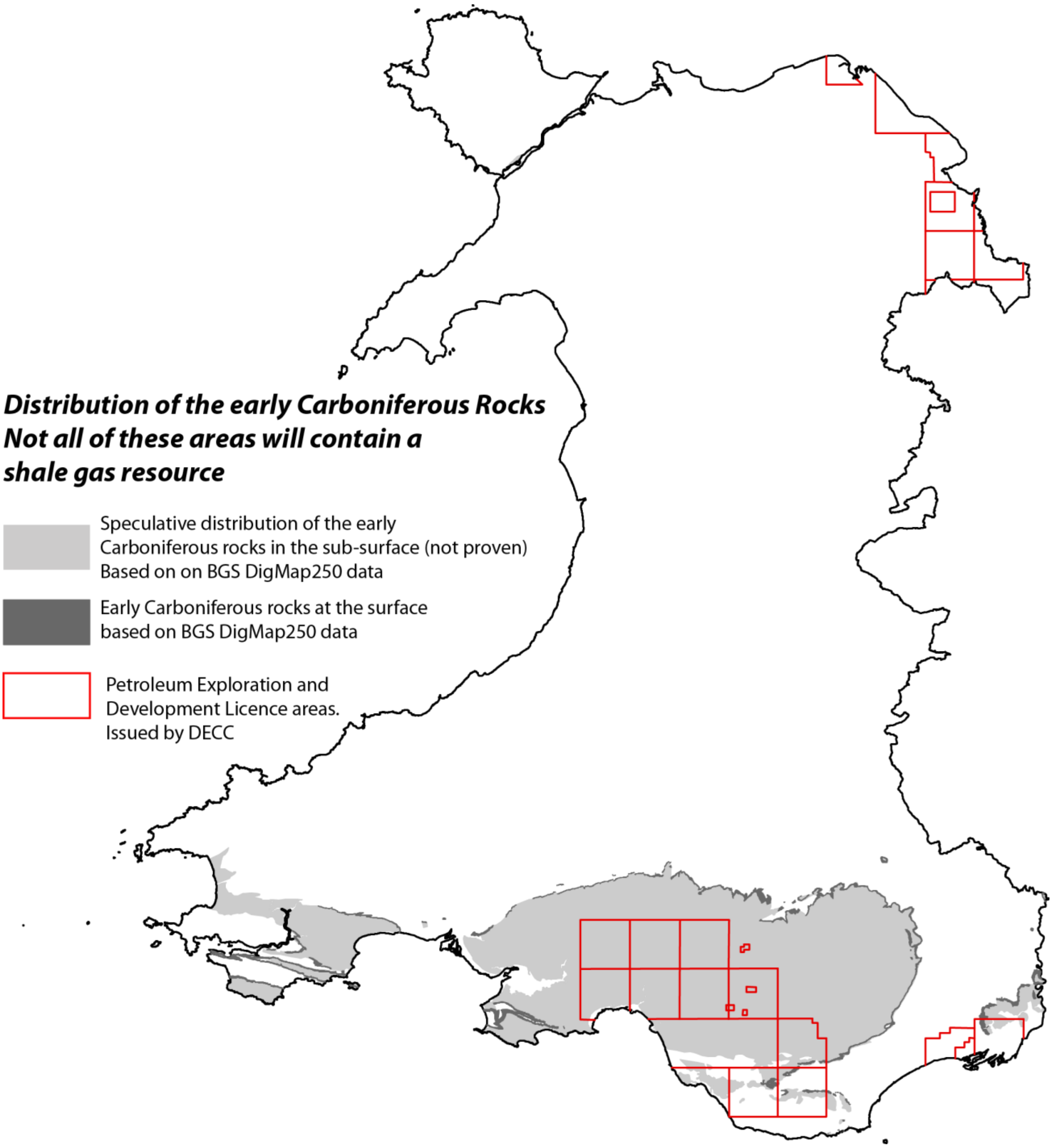


Figure 8 Distribution of early Carboniferous rocks

Lower Palaeozoic shales

Most of Wales is underlain by rocks of Lower Palaeozoic age which are widely exposed at the surface (Figure 9). Although these have not been the subject of exploration and their prospectivity is not proven, there are a number of factors which indicate potential prospectivity.

Hydrocarbon generation from rocks of this age are known from sedimentary basins around the Atlantic margin. These include the Laurentian Basin of North America (Longman and Palmer, 1987; Thickpenny and Leggett, 1987; Leggett, 1980; Ryder, 2008) where the Utica Shales are a significant shale gas play. Although units of similar age and recording similar geological events are present in Wales, research is required to establish whether they are prospective.

Most of the potentially prospective formations comprise marine, coastal or deltaic mudstones deposited during times of reduced oxygenation at the water-sediment interface. Analysis indicates that these dysaerobic facies occur at specific intervals throughout the geological history of Wales and this can be used to predict their distribution.

In order to understand their distribution, a systematic review of these potentially carbonaceous mudstones in Wales and comparison with available evidence for prospectivity was undertaken by the BGS (Kendall, 2013; Figure 9). Because there is very little geophysical (downhole or seismic reflection) data available for Wales to indicate how potentially prospective units extend into the subsurface a detailed volumetric resource assessment of the geological units was not attempted. Instead a first order lithological assessment based on the field descriptions, stratigraphic and conceptual geological models was undertaken. This study concluded that, although organic rich mudstones are widespread at surface in central and North Wales, some may be overmature for gas, there is little evidence for their subsurface extent, organic content, and maturity, and that structural complexity may be a significant barrier to exploration.

Although there are no commercial resource or reserves estimates available for shale gas from the Lower Palaeozoic rocks of Wales, there has been some limited drilling and seismic reflection acquisition in the Welsh Borders for conventional hydrocarbons. Conoco acquired 2D seismic reflection lines during the 1960s, which led to exploration near the Malverns. These wells provided encouraging results but were not developed further (Smith 1987; 1993; Parnell 1987a, b). Several companies were awarded licences. Sovereign Oil and Gas drilled two wells: Usk 1 and Fownhope 1 the former of which reported evidence of gas.

In summary, the Lower Palaeozoic carbonaceous shales in Wales have been the focus of only very limited research and the initial indications are that there may be potential for hydrocarbons. They are considered to be a very high exploration risk in terms of chance of success, requiring a large investment in subsurface investigations (seismic reflection lines and boreholes with cores and geophysical logging) to quantify any resource potential.

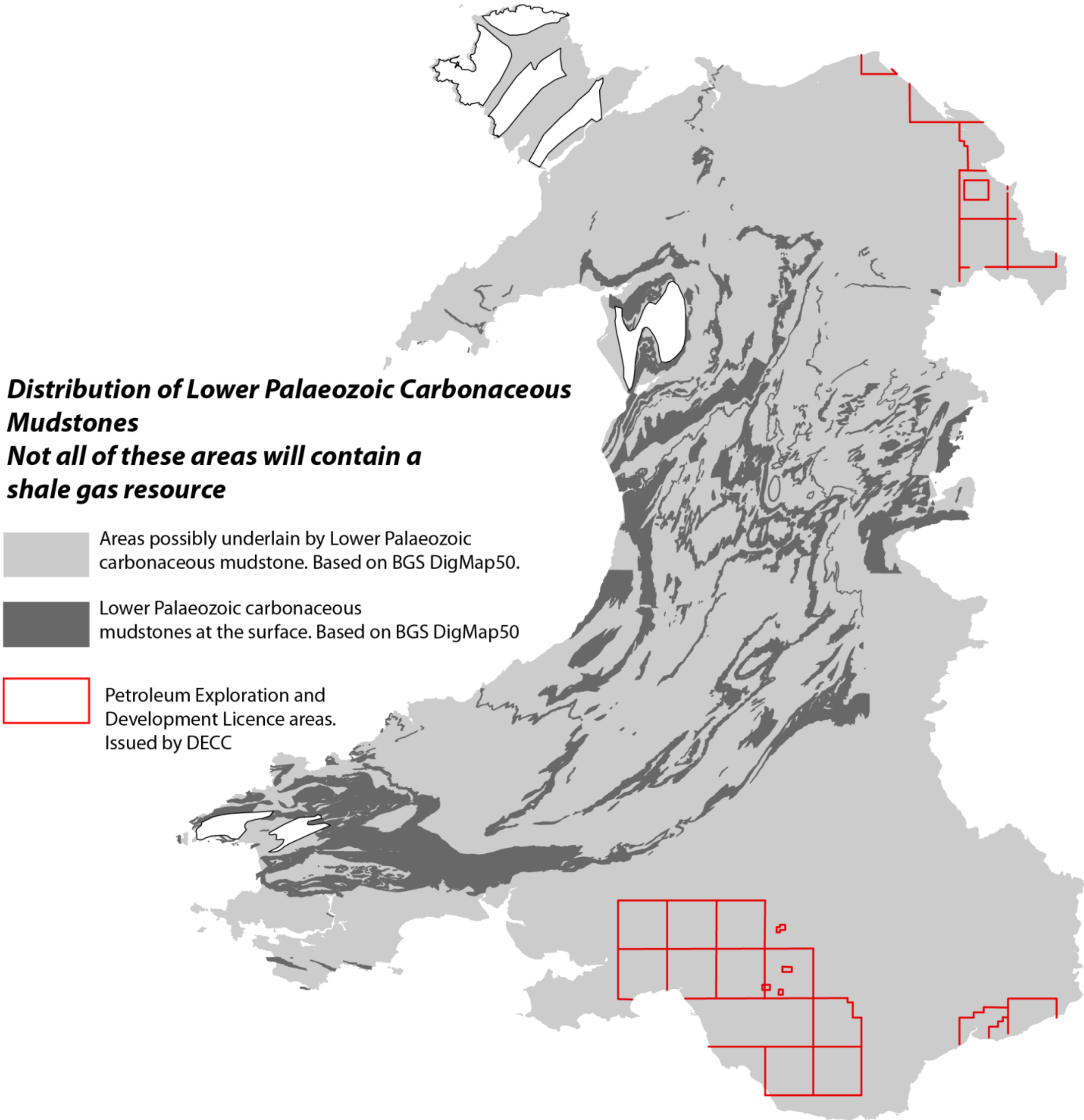


Figure 9 Lower Palaeozoic Carbonaceous mudstones (after Kendall, 2013)

3.4 SHALE GAS EXTRACTION TECHNIQUES

Shale gas extraction techniques can differ between exploration and production wells and can be tailored to maximise productivity in different geological strata and geographical settings. In an account of a UK shale gas exploration drilling operation, Cuadrilla Resources described the site where a well is drilled from a single pad occupying around 7,000 m^2 that could support up to 10 wells, spaced out across the site area (Regeneris, 2011). In their review of unconventional hydrocarbons, the Australian Council for Learned Academies described individual sites as accommodating storage facilities for water and proppants used for drilling, storage and/or treatment of produced water, gas processing and power supply or distribution. They will also have to be served by transport infrastructure such as roads, rail lines, pipelines, overhead or buried power lines and possibly docks (Cook et al., 2013 and references therein).

Typically, a borehole is drilled from the surface to a depth below the base of any aquifer rocks. Casing is then inserted into the borehole and cement is then pumped between the casing and the borehole walls to effectively seal the borehole from the surrounding rocks and any fluids the rocks may contain. This is done to prevent contamination of water supplies and also as a foundation for equipment required to produce the gas once the well is completed. The requirement for a high standard of well completion to mitigate the potential hazards has been recognised (The Royal Society And The Royal Academy Of Engineering, 2012). Drilling is then recommenced to the required depth. A technique known as directional drilling is employed to angle the borehole away from the main pad area, out into the shale layer. Each well can support multiple boreholes spurred off and radiating away from main well. This ensures that the maximum volume of shale can be drained from a single well pad.

When drilling is completed, the drilling equipment is removed from the wellbore and casing is inserted. The casing is tested to ensure well integrity and that the case is capable of preventing hydrocarbons from seeping into the surrounding rocks.

Next a perforating gun is lowered to the production horizon. Electrically triggered, a charge perforates the casing, cement and shale. Next, the hole is hydraulically fractured. This is achieved by isolating a section of the borehole and pumping water, proppant (sand or synthetic polymer beads) and additives into the well bore and casing at high pressure, causing the shale to fracture. The mixture is forced into the fractures, propping the fractures open and creating the pathways for the gas to flow. This process may be repeated a number of times to maximise the area of shale to produce gas. Following this process is a phase of testing and monitoring before gas is allowed to flow up to the well head for production (Jenkins et al., 2008).

3.5 SCOPE FOR FURTHER RESEARCH SURROUNDING IDENTIFYING AND QUANTIFYING SHALE GAS RESOURCES IN WALES

The main barrier to assessing the shale gas resource in Wales is lack of relevant data. Resource assessments require seismic reflection data and borehole data with which to build a model of the subsurface.

Seismic reflection data provides an indication of the structure of the rock layers beneath the surface. This is required to understand the depths below ground level at which potentially prospective units occur. This data also allows the thickness of prospective units to be estimated, which contributes to volume estimates and resource or reserves estimates.

Boreholes can also help to confirm rock layer thicknesses, using geophysical logging techniques, from which rock properties including organic content and mineralogy can be inferred or calculated. When drilling boreholes, sections or the whole of the borehole may also be cored, giving materials to test, correlate and constrain the interpretations made from geophysical techniques.

Section 4 gives an overview of other issues surrounding unconventional gas exploration and production. These include seismic hazards, the management of radioactive waste and in the management of water resources.

4 Geological and environmental issues surrounding the exploration and development of unconventional gas resources

The recent environmental review undertaken by DECC (Department of Energy and Climate Change, 2013b) states that “through the use of construction and operation best practice, environmental effects resulting from licensing of onshore exploration and production activities could be minimised and managed to be acceptable to regulators, decision makers and communities”. This review included a range of environmental issues surrounding the exploration and production of unconventional gas resources. These include the risk of earthquakes associated with hydraulic fracturing, the management of water resources and quality associated with drilling and fracturing operations and the potential for contamination of groundwater and surface water. Some shales can also be naturally radioactive, leading to the necessity to handle and manage the disposal of waste generated by unconventional gas exploration/development appropriately.

All of these issues are described in this section and gaps in understanding are highlighted.

4.1 WATER REQUIREMENTS

Unconventional gas exploration and development has two main implications for water resources: water supply and potential pollution of groundwater or aquifers. This section describes water resource terminology and the options for resourcing water for exploration activities. The potential pathways for contamination are also described in 4.2.

Water sources

Exploratory and production boreholes for unconventional gas both require water. Injection water for shale gas developments could potentially be sourced from public supply (the ‘mains’) or an ad hoc licensed or an unlicensed water supply, sourced in turn from groundwater and/or surface water.

Groundwater is defined as ‘all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil’. Aquifers are defined as ‘a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater’(WFD2000/60/EC). Groundwater is an important resource, supplying both public and private water supplies and supporting agricultural, leisure and industrial water users. It is also essential for supporting baseflow in rivers and a range of groundwater dependent ecosystems.

Natural Resources Wales designates aquifers either as a principal or a secondary aquifer. Areas that are not aquifers are designated as unproductive strata. The vast majority of Wales is designated as secondary aquifer with a smaller area designated as principal aquifers (Figure 10). There are no geological formations classed as unproductive aquifers in Wales (British Geological Survey, 2010).

Groundwater abstractions may include boreholes, wells, springs, and adits. Water abstraction data from 2000-2012 reported to DEFRA shows that in Wales an average of 2.27% of public drinking water comes from licensed groundwater abstractions, the remaining 97.73% is from surface water (rivers and reservoirs). Groundwater is also abstracted for industrial, agricultural and leisure activities, with abstractions over 20 m^3/day of 20,000 litres/day requiring a licence from Natural Resources Wales.

There are currently 17,700 registered private water supplies in Wales that supply 166,000 people that either live or work in premises that rely on a private water supply (Drinking Water

Inspectorate, 2012). Due to the low yielding nature of aquifers across west, mid and north-west Wales these areas were designated in the late 1960s (via Statutory Instrument), as 'exempt' from groundwater abstraction licensing however this exempt area is due to be removed during 2014.

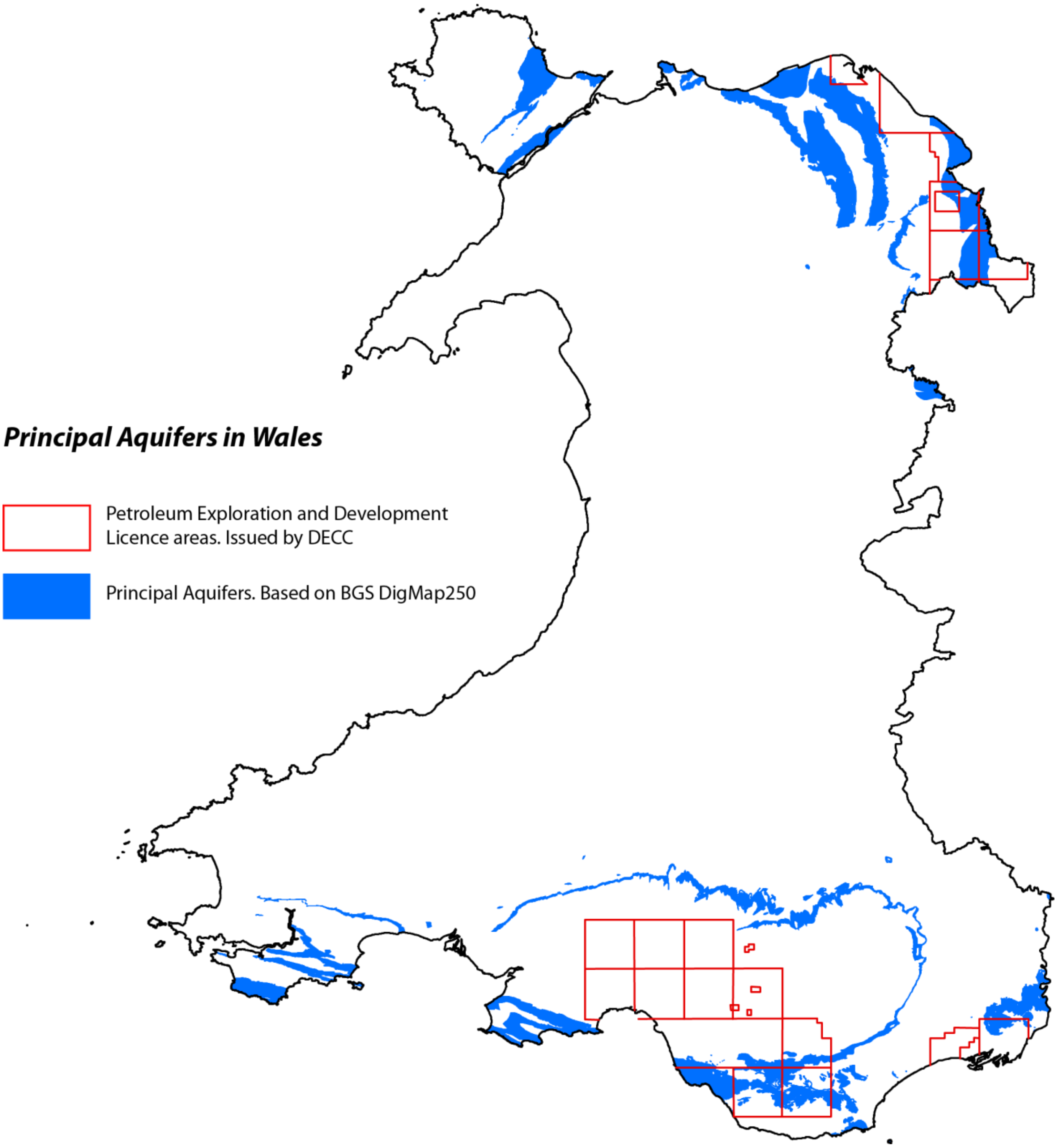


Figure 10 Surface exposure of principal aquifer rocks (blue) in Wales comprising of the Carboniferous Limestone across Wales and the Permo-Triassic sandstones in north-east Wales. The remaining uncoloured area is classified as Secondary aquifer

Water requirements for exploration and development

Exploratory and production boreholes both require water. The volumes of water used for drilling and hydraulic fracturing will be different for each well. Water is utilised during drilling of the vertical and directional components and a well may require between 250–2,300 m^3 of water for drilling fluids. It is estimated that between 8,400–23,000 m^3 of water are also required for hydraulic fracturing of each well (Table 6).

Shale Play	Drilling (m^3)	Fracking (m^3)	Total (m^3)
Barnett (US)	950	14000	14950
Haynesville (US)	2300	19000	22300
Fayetteville (US)	250	19000	19250
Marcellus (US)	400	21000	21400
Eagle Ford (US)	500	23000	23500
Bowland Shale (UK)*	900	8400	9300

Table 6 Estimated water requirements per well for drilling and fracturing in different shale gas plays (from Mantell (2011) and Cuadrilla Resources (2012)*)

**Values for the well drilled at Preese Hall is also given but it should be noted that this is exploratory borehole and not has not been hydraulically fractured for production.*

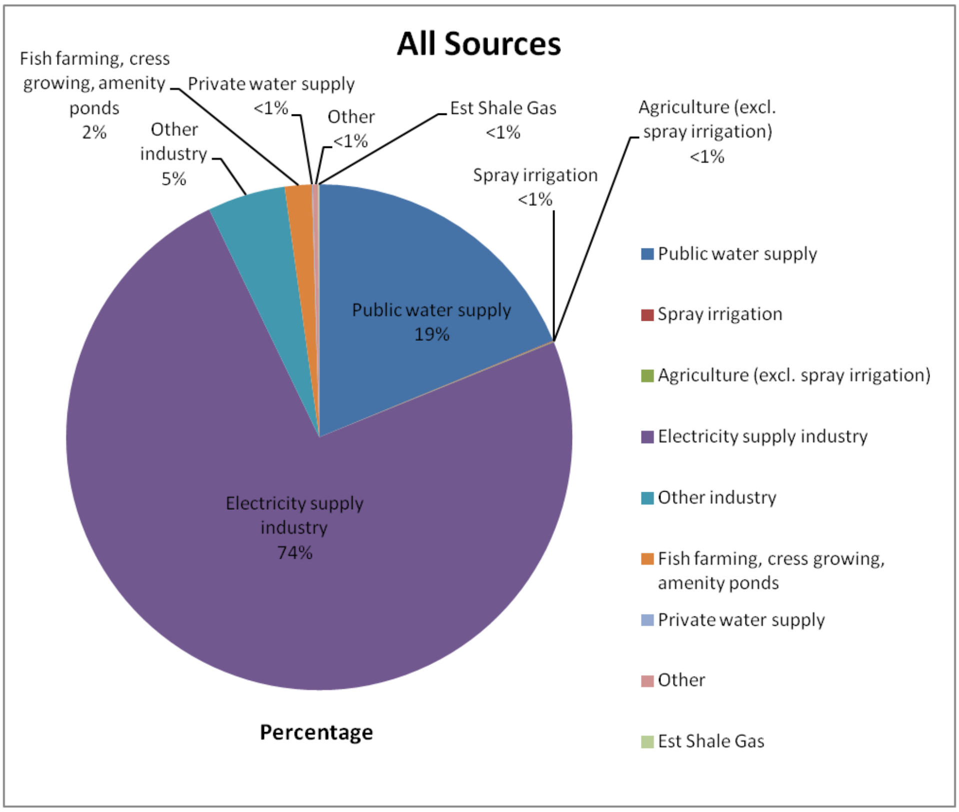


Figure 11 Water requirements for 1 well (example number of wells) expressed as a percentage of the total licence water abstraction for all users in Wales (licensed abstraction volumes averaged between 2000-12)(Department of Food and Rural Affairs, 2013).

The requirement for water for hydraulic fracturing and drilling is difficult to accurately predict because it is not known how many wells will be drilled in a given period. Assuming that 1 wells is drilled in one year, the upper estimate for the water required would be 23,500 cubic metres (Table 6). For Wales, the Environment Agency list an average annual abstraction of 3,523 million cubic metres for the period 2000-2012. (Department of Food and Rural Affairs, 2013) On this basis, the requirement for hydraulic fracturing and drilling for an individual well would be less than 0.0007% of the total annual licensed water abstraction in Wales (Figure 11). A single multi-year shale gas production project is likely to consist of a number of wells each supporting a number of horizontal wells. In their review, in the Institute of Directors consider what shale gas production could potentially look like. They give two example projects which would be multi-year projects. The first assumes 10 well pads with 10 laterals and a larger example site of 10 well pads with 40 laterals (Institute of Directors, 2013). Taking the first example from the Institute of Directors report (2013) of 10 well pads with 10 laterals, the requirement for hydraulic fracturing and drilling would be 0.07% of the total annual licensed water abstraction in Wales.

Providing a licence to abstract groundwater is obtained from Natural Resources Wales then the processes involved in licensing will consider both the sustainability of any new groundwater abstraction and potential impact on existing abstractions and the environment. There is a risk that within the exempt area of Wales a developer could legally abstract as much water as they require without any licences or assessment by Natural Resources Wales, however the exemption is due to be removed in 2014, at which point all abstraction exceeding $20m^3$/day will need to be appropriately licensed. The demand for water resources will be localised in the areas where shale gas exploration and development is being carried out.It is in these areas where the assessment of water resources must be considered to ensure the sustainability of the available groundwater resource. Guidance on groundwater abstraction licensing is given in “onshore oil and gas exploration in the UK: regulation and best practice – Wales” document, produced by Department of Energy & Climate Change for information on Groundwater abstraction licensing (DECC, 2013b).

4.2 POTENTIAL CONTAMINATION RISK TO GROUNDWATER

Drilling and production of unconventional gas is likely to involve interaction with groundwater, as boreholes pass through groundwater-bearing rocks to reach gas resources below. Rozell and Reaven (2012) identified five pathways for potential water contamination: transportation spills, well casing leaks, leaks through fractured rock (Davies et al., 2013), drilling site discharge, and wastewater disposal.

Guidance and best practice for onshore oil and gas exploration are provided as a roadmap document (DECC, 2013b) where key actions, legislation and guidance are provided. In addition the UK Onshore Operations Group (UKOOG, 2013) provides more detail on the industry-led regulatory compliance, well design and construction and environmental management to manage the risk of aquifer contamination.

Hydraulic fracturing fluids

Drilling and hydraulic fracturing requires the use of chemicals that, need to be contained in order to avoid contamination of the surrounding groundwater.

The fluids used in drilling and fracturing, whilst principally comprised of water, contain other additives, some of which are not normally naturally occurring in the places where drilling is taking place. Hydraulic Fracturing fluid is primarily water (~95.4%) with sand or other proppants (~5%) added to help keep fractures open, and chemical additives (<0.2%) to improve operational performance. These additives include, scale inhibitor, acid, biocide, friction reducers and surfactants (Figure 12). The additives have various roles and are essential for effective shale gas reservoir stimulation (Stuart, 2012).

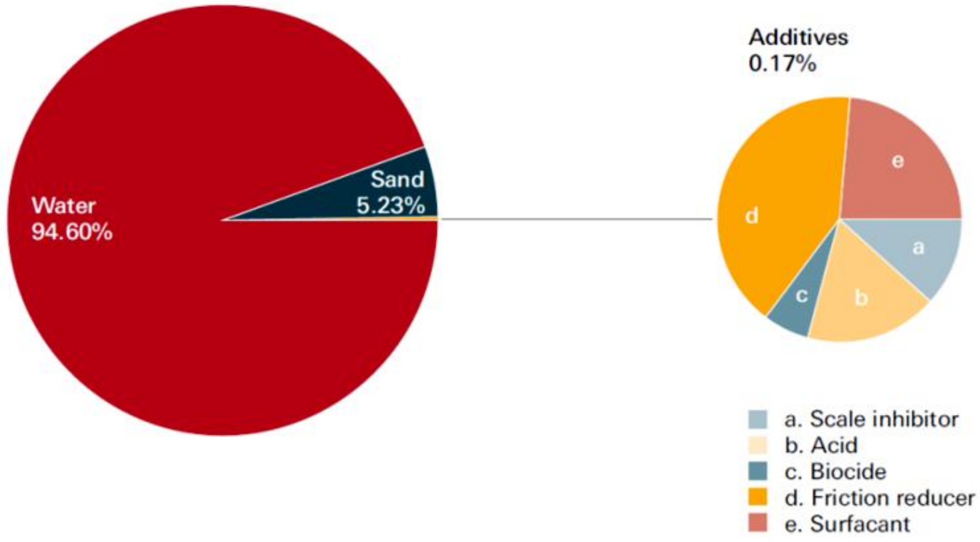


Figure 12 Typical composition of fracturing fluid by volume. Data taken from multiple published/unpublished sources (The Royal Society and The Royal Academy Of Engineering, 2012)

In order to manage contamination risk, operators in Wales will be required to supply detailed information on the composition of hydraulic fracturing fluids to Natural Resources Wales before authorisation is granted (Department of Energy and Climate Change, 2013c). The WFD (2000/60/EC) and the Groundwater Daughter Directive (2006/118/EC) require member states to protect groundwater against pollution by limiting entry of pollutants. These pollutants are divided into hazardous substances that must be prevented from entering groundwater and non-hazardous substances that must be limited. The joint agencies Groundwater Directive Advisory Group or 'JAGDAG' provides further advice and clarification on the determination of the status of numerous hazardous and non-hazardous substances.

Pathways

There are a number of potential pathways in which fracturing fluid could contaminate the surrounding groundwater. A review by the Royal Academy of Engineers (The Royal Society And The Royal Academy Of Engineering, 2012) highlighted that pathways can include fractures created or enhanced by human activities (Davies et al., 2013). These include hydraulic fracturing, or result from the failure of a well (eg damage to the well casing or poor well completion).

Bedrock contains naturally occurring pathways along which fluids and gas can flow, such as fractures and fissures in the bedrock which are more common at the surface and close up at depth due to pressure of the overlying rocks. Hydraulic fracturing fluids, flowback fluids (fluid returned to the surface after drilling and hydraulic fracturing), produced water (displaced formation water) or displaced methane (and other gases) could potentially contaminate groundwater if migration pathways are naturally present or induced through industrial processes (eg drilling or hydraulic fracturing).

Flowback fluid is the water that is returned to the surface after drilling and hydraulic fracturing has been undertaken. The flowback fluids comprise a mixture of fluids used in the drilling and hydraulic fracturing and 'formation' water from the target shales. The formation fluid constituents can vary depending on the local geology. The majority of flowback fluid is recovered in a matter of several hours to a couple of weeks (Stuart, 2012). Over time the composition of flowback increasingly reflects the composition of the formation water and is then referred to as ‘produced water’.

Produced water can contain toxic organic compounds, heavy metals, naturally occurring radioactive materials and highly mineralised (saline) groundwater. The volume of produced water may account for between 30% and 70% of the original fracture fluid volume. However, flow back of fracture fluid in produced water can continue for several months after gas production has begun (Groundwater Protection Council and ALL Consulting, 2009).

Leakage of methane from unconventional gas operations is also a potential risk to groundwater quality. Although no peer reviewed studies have been published in the UK, research in Pennsylvania, USA (Révész et al., 2012; Osborn et al., 2011) show that there are identifiable isotopic differences between both biogenic and thermogenic methane. The isotopic differences can be used to show how deep thermogenic methane may have migrated upwards into shallow groundwater and ultimately into water supply wells. Conversely, Molofsky et al (2011); Warner et al (2013) and Jackson et al (2013) all dispute that methane in groundwater can be reliably associated with hydraulic fracturing operations and the subject is still a matter of academic dispute. The Royal Society review (The Royal Society And The Royal Academy Of Engineering, 2012) recommended that monitoring should be carried out before, during and after shale gas operations so any changes against a natural methane baseline can be identified. In Wales the BGS has initiated baseline monitoring of methane in groundwater within the Vale of Glamorgan.

The production of coal bed methane may require the dewatering of large areas to enable extraction. Dewatering has the potential to induce interaction between layered aquifers and have an impact on water supplies, river baseflows and groundwater dependent wetlands. Dewatering for CBM may also involve a requirement to handle and dispose of large volumes of potentially contaminated mine (ground) water (Jones et al., 2004).

Disposal

Once the flowback or produced water is returned to the surface there are a number of available options for operators to manage the disposal or reuse of the fluids. The operator could pay a licensed contractor to remove and treat the water or obtain an environmental permit from NRW for disposal of the flowback fluid. A closed loop system could also be used to re-use drilling fluids typically utilising steel storage tanks to hold the fluids (Stuart, 2012). The “Onshore oil and gas exploration in the UK: regulation and best practice – Wales” document, produced by Department of Energy & Climate Change, gives information on disposal of waste water (DECC, 2013b).

Scope for further research

Groundwater resources: Wales has been divided into ‘groundwater bodies’ that are effectively management units for the assessment and reporting of groundwater status for the WFD. The majority of groundwater bodies in Wales have been classified by Natural Resources Wales as being in good quantitative status (i.e there is water available to abstract). Where unconventional gas development requires water abstraction or dewatering, consideration should be given to the amount of water that is available for abstraction within a given groundwater body. Where developments are likely to occur in the exempt area, (which will be removed in 2014) it is likely that our knowledge on the available groundwater resource is much less. Resource survey and data collection may be required to assess if there is enough groundwater available to support proposed abstractions.

Aquifer properties and structure:

There is limited knowledge on the hydrogeological properties of formations occurring between potential source rocks at depth and the overlying aquifers. The properties of these rock units are important for characterising how interaction between the source rock and aquifer could occur. Due to paucity of data there is currently significant uncertainty of the depth to and nature of the base of many of the aquifers in Wales, which is important for understanding aquifers in 3D and in relation to any potential source rocks at depth.

Geochemical baseline studies and deep formation water:

Detailed geochemical baseline studies in Wales in areas that could be affected by the development of unconventional gas operations are limited. Baseline groundwater geochemical information is vital to assess risks and impacts from any unconventional gas exploration activity. In addition to the shallow geochemical baseline there is limited information on the deeper formation water, which may need to be removed and treated as part of any operation.

Groundwater methane baseline: The BGS Baseline methane survey of UK groundwaters project has collected a limited number of initial samples in the South Wales area in conjunction with Natural Resources Wales. By collecting samples for methane from exiting groundwater monitoring boreholes, we are able to understand the 'baseline' concentrations. Importantly baseline data allows us to evaluate any future change in methane concentration that may take place as a result of unconventional gas exploration and other activity in the subsurface. This methane baseline data collection was very limited in its coverage and has only been undertaken in parts of South Wales. Large areas of Wales are currently without data.

4.3 EARTHQUAKE HAZARD FROM UNCONVENTIONAL GAS EXPLORATION AND PRODUCTION

Background

It is relatively well-known that anthropogenic activity can result in man-made or “induced” earthquakes. Although such events are generally small in comparison to natural earthquakes, they are often perceptible at the surface and some have been quite large. Underground mining, deep artificial water reservoirs, oil and gas extraction, geothermal power generation and waste disposal have all resulted in cases of induced seismicity. Davies et al (2013) presented a review of published examples of earthquakes induced by a variety of activities. Ellsworth (2013) gave a useful overview of injection-induced earthquakes. A Royal Society and Royal Academy of Engineering report (2012) examined the risks associated with hydraulic fracturing during shale gas exploration and production. A report commissioned by the Department of Energy and Climate Change (Green et al, 2012) set out a number of recommendations for the mitigation of seismic risk in future hydraulic fracture operations for shale gas. These recommendations were adopted as part of the regulatory framework for future operations in a written ministerial statement to Parliament by the Rt. Hon. Edward Davey (Energy Secretary).

The aim of hydraulic fracturing is to improve fluid flow in an otherwise impermeable volume of rock. This is achieved by injecting fluid at a sufficient pressure to cause tensile failure (cracking of the rock) and develop a network of connected fractures to increase permeability and provide conduits for gas flow. Hydraulic-fracture induced micro-seismicity is in fact desirable and has been widely used in the oil and gas industry over the past decade to image fracture networks and estimate the orientation and size of a stimulated volume (Rutledge and Phillips, 2003). The dominant mechanism for creation of the microseismic events is shear slippage, induced by increased pore pressures along pre-existing fractures (Pearson, 1981).

Magnitudes of the induced earthquakes during hydraulic fracture stimulation in hydrocarbon fields such as the Barnett Shale (Maxwell et al., 2006) and the Cotton Valley (Holland, 2011) are typically less than 1 ML, which means that these events are not detected, unless a local monitoring network is in place. Over 100,000+ stimulations have been carried out in the U.S. in the past decade and felt seismicity is extremely rare. However, more recently, there have been a few examples of rather larger induced earthquakes during hydraulic fracturing operations. In the Etsho and Kiwigana fields in Horn River, Canada, 216 earthquakes were detected during in 2009-2011 (British Columbia Oil and Gas Commission, 2012). The largest event had a magnitude of 3.8 ML and, to date, this is the largest known earthquake induced by hydraulic fracture operations in a hydrocarbon field anywhere in the world. In the Eola Field, Garvin County, Oklahoma, 43 earthquakes were detected during hydraulic fracturing in 2011 with magnitudes up to 2.8 (Holland, 2011). In Lancashire, UK, 58 earthquakes were linked to fluid injection during hydraulic fracturing at the Preese Hall well in 2011 (de Pater and Baisch, 2011). The largest had a magnitude of 2.3 and was felt locally. These hydraulic fracture treatments were carried out during exploration of a shale gas reservoir in the Bowland basin, Lancashire. As a result of the earthquakes, operations were suspended at Preese Hall.

Mechanism for Induced Earthquakes

Earthquakes generally result from slip along a pre-existing fault in the Earth. The slip is triggered when the stress acting along the fault exceeds the frictional resistance to sliding. The critical conditions are quantified by the Coulomb criterion, which embodies two fundamental concepts, friction and effective stress. This can be illustrated by considering the shearing of a split block, (Figure 13). The block is subjected to a normal force, F_n, and a shear force, F_s, which can be translated into a normal stress, σ, and the shear stress, τ, acting across and along the fault at *A*. Slip is triggered when the shear stress T is equal to the frictional strength $\mu(\sigma - p)$, where $(\sigma - p)$ is the effective stress and μ is the coefficient of friction. The presence of fluid at pressure, *p*, on the fault surface will reduce the effective stress on the fault.

In the three cases of induced seismicity during hydraulic fracturing operations given above, significant earthquakes resulted because the injection of fluids during hydraulic fracturing increased fluid pressure in a nearby fault zone, reducing effective stress on faults.

The pre-existing state of stress on most faults is unknown, though if a fault is close to failure it may only require a small stress perturbation to cause it to fail. These faults would fail at some point in future as more stress accumulates, but the reduction in the effective stress caused by an increase in pore fluid pressure can bring that failure forward in time.

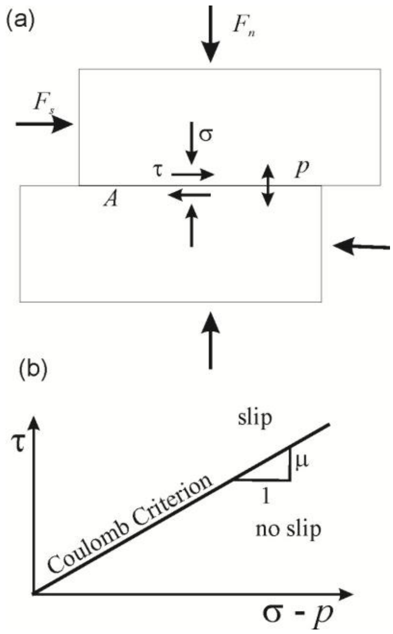


Figure 13. Shearing of a jointed block subjected to normal force, F_n and shear force F_s, with fluid inside the joint at pressure *p*. Slip along the joint is triggered when the shear stress T is equal to the frictional strength $\mu(\sigma-p)$, where $(\sigma-p)$ is the effective stress and μ is the coefficient of friction.

Controlling factors

In general, the seismicity induced by hydraulic fracturing depends on a number of factors. The first of these is the strength of rocks in the geological formations of interest. Most potential shale gas reservoirs occur at shallow depths in relatively weak rocks, whereas the larger tectonic events tend to nucleate at much greater depths where the Earth's crust is significantly stronger.

A second factor is the size and state of stress of any faults in the area likely to be affected by fluid injection. Earthquake magnitude scales with fault area, for example, an earthquake with a magnitude of 2 might typically occur on a fault that is 100m long, whereas magnitude 5 earthquakes require fault dimensions of several kilometres. The pre-existing state of stress on a fault determines how close it is to failure. Faults that are critically stressed may require only a small stress perturbation to cause them to fail. A critical state of stress is widely expected at depth and observed throughout the Earth's crust (Townend and Zoback, 2000).

A third factor is the pressure change induced by the hydraulic fracture process (Zoback, 2012). In turn, this is affected by the volume of injected fluid and the rate of injection. Larger volumes and higher injection rates generate higher pressures. For the volumes of fluid used in shale gas exploration and production, the pressurization during hydraulic fracturing affects only limited volumes of rock (typically several hundred meters in extent) and pressurization typically lasts only a few hours. This restricts the spatial extent to the volume affected by a pressure change, to a region close to the point of injection. More distant faults are unlikely to be affected by such operations.

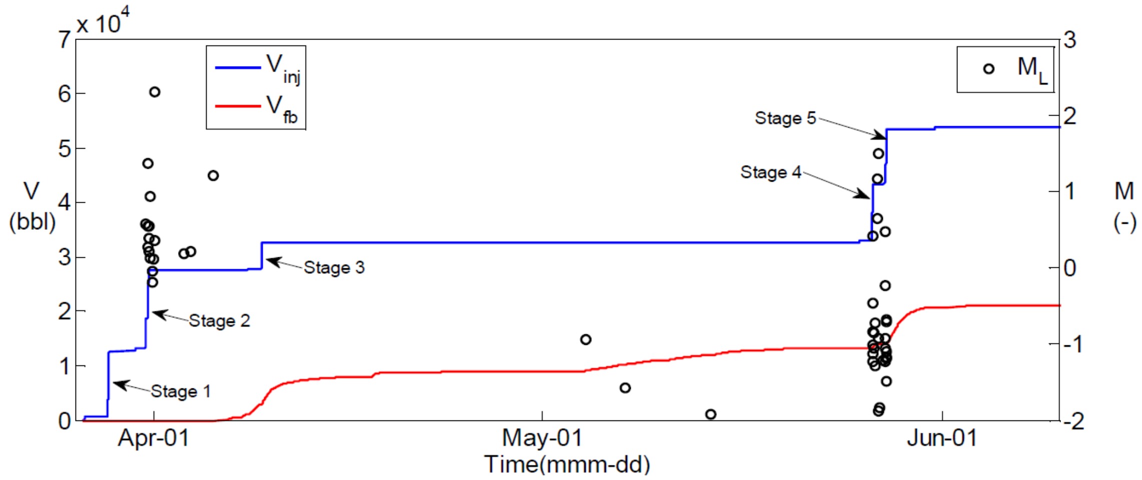


Figure 14. Volume of injected fluid (blue line) and earthquakes (black circles, scaled by magnitude) during hydraulic fracturing operations at Preese Hall, Blackpool, between March and June 2011 (from de Pater and Baisch, 2011). There are five distinct treatment stages. Earthquake activity closely correlates with stages 2 and 4. The largest event with 2.3 ML at 02:34 on 1/4/2011 occurred shortly after stage 2. The red line shows the flow back volume.

In general, the number of fluid injection induced earthquakes above a given magnitude will increase approximately proportionally to the injected fluid volume (Shapiro, 2003; 2012). It is clear from the observations of the induced seismicity at Preese Hall, Blackpool in 2011 (Figure 14) that earthquake activity closely correlates with stages 2 and 4. No observed seismicity was associated with those stages in which smaller volumes of fluid were used.

By contrast, if waste water from hydraulic fracturing operations is disposed of by re-injection, significantly larger earthquakes could be induced because of the larger volumes of fluid involved in this process. There are numerous examples of earthquakes induced by disposal of fluids in deep wells (e.g. Frohlich et al., 2011). In central and eastern US more than 300 earthquakes with M ≥ 3 occurred in the 3 years from 2010 to 2012, whereas the average number/year from 1967 to 2000 is 21 (Figure 15). There are numerous examples of earthquakes induced by disposal of fluids in deep wells. A magnitude 4.0 earthquake on 31 December 2011 in Youngstown, Ohio, appears to have been induced by injection of wastewater in a deep well. A magnitude 4.7 earthquake in central Arkansas in 2011 has also been linked to deep injection of wastewater. In 2011, a magnitude 5.7 earthquake in central Oklahoma was located close to active wastewater-injection wells.

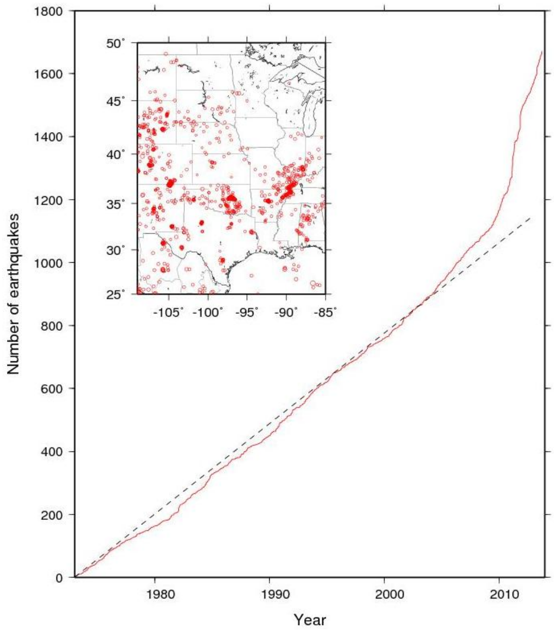


Figure 15. Cumulative count of earthquakes with M ≥ 3 in the central and eastern United States, 1967–2012 (after Ellsworth, 2013). The inset shows a map of the earthquake activity.

Hazard

The possibility of other earthquakes during future hydraulic fracture operations in the UK can't be ruled out given that it is quite possible that there are other critically stressed faults in areas with shale gas potential. However, the hazard from these earthquakes is likely to be rather low in terms of the probability of damaging ground motions and the spatial extent of the areas affected.

In the UK, maximum observed magnitudes from coal mining induced seismicity (Bishop et al., 1994; Redmayne et al., 1988, 1998), rather than the maximum magnitudes for tectonic events (Main et al., 1999), may provide a realistic upper limit for shallow injection induced events. These coal-mining events (Figure 16) occur in the same Carboniferous geological formations from which shale gas is now being sought. The maximum magnitude for such events at which a statistically significant number of events have been recorded is magnitude ~3 ML. An event of this size at a depth of 3 km is unlikely to cause structural damage, but such an event could be strongly felt at intensities of 4-5 EMS and could cause some alarm to local residents. There are examples of mining-induced earthquakes of similar magnitudes in the UK that caused superficial damage (Westbrook et al., 1980; Redmayne, 1998), however, there have been no reports of structural damage from mining-induced earthquakes in the UK in the past forty years.

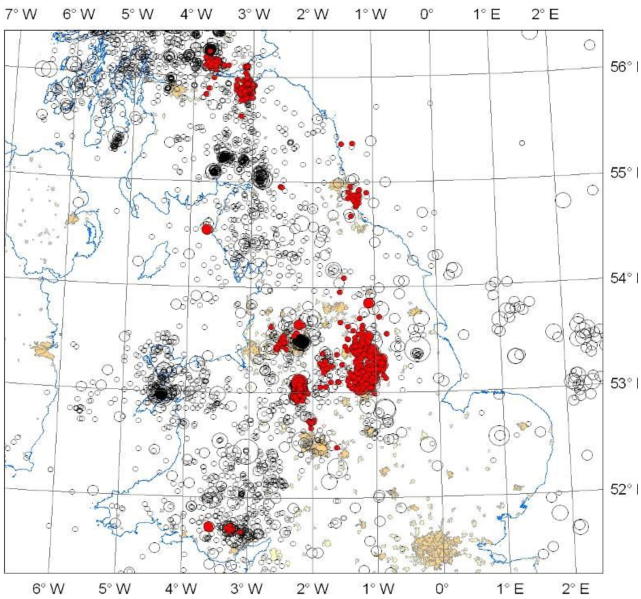


Figure 16. Mining induced seismicity in the UK (red circles) alongside natural earthquake activity (open circles)

Mitigation

The first step to minimize the possibility of significant induced seismicity is to avoid injection into active fault zones and faults in brittle rock. This may require a more accurate model of the sub-surface geology than is presently available in some areas.

Secondly, since the number of fluid injection induced earthquakes depends on the injected fluid volume and formation pressure, reducing the volume of fluid and implementing flow back, where appropriate, can also reduce the probability of significant earthquakes.

Experience of induced seismic activity in Enhanced Geothermal Systems (EGS) has led to the development of so-called "traffic light systems" linked to real-time monitoring of seismic activity (Majer et al., 2008). Such systems may be considered as "industry best practice" and form an essential mitigation strategy for hydraulic fracturing operations. The traffic light system has three levels: green, where injection proceeds as planned; amber, injection proceeds with caution, possibly at a reduced rate; and, red, injection is suspended immediately. However, such a system requires the definition of acceptable limits for the cessation and recommencement of operations. In addition, an effective monitoring system needs to provide reliable automatic locations and magnitudes in near real-time for very small events in the magnitude range -1 to >1 ML.

Hydraulic fracture growth and direction can be monitored during the fracturing process using industry standard microseismic monitoring using either an array of surface or down-hole sensors. Tiltmeters can also be used. Monitoring of upward fracture growth and containment can be carried out by complementary diagnostics such as temperature or tracer logs.

More generally, to better understand the hazard of induced earthquakes associated with future shale gas operations, seismic hazards should be assessed prior to proceeding with any exploration or production. This should include:

1) Appropriate baseline seismic monitoring to establish background seismicity in the area of interest.

2) Characterisation of any possible active faults in the region of interest using all available geological and geophysical data.

3) Application of suitable ground motion prediction models to assess the potential impact of any induced earthquakes.

Scope for further research

Our knowledge of fault systems in the sub-surface is limited to areas where detailed surveys have been carried out. Even in areas of the UK where seismic activity has already been recorded it is often difficult to associate earthquakes with specific faults given the uncertainties involved. In addition, the pre-existing state of stress and pore pressure acting on a fault are also usually unknown. So although effective-stress models provide a basis for modelling induced earthquakes, the initial conditions to constrain this model are generally lacking. We also often lack knowledge about the hydrological properties of the sub-surface. This limits the use of geomechanical modelling methods. Measuring the initial stress state and pore pressure, tracking the injection history, and careful seismic monitoring may help improve understanding.

Seismological methods alone cannot discriminate between man-made and natural tectonic earthquakes. In some cases induced earthquakes may occur close to the source of the pressure perturbation, but at other times, they may take place many kilometres away. Similarly, sometimes induced events occur shortly after the industrial activity begins, but in other cases they happen long after it has ceased. This is demonstrated by the fact that coal mining induced earthquakes continue to be recorded in the UK long after mining has stopped in many areas.

The statistical relationships observed in natural seismicity may not necessarily apply to induced seismicity. This has implications for maximum expected magnitudes and more research is needed to better understand this. More work is also required to better understand the relationship between well pressures and seismicity induced in shale. Although it is generally thought that the number of induced earthquakes above a given magnitude is directly related to the volume of injected fluid, this relationship can be complex. For example, Brodsky et al (2013) show that seismicity rate positively correlates with the net volume of produced fluid (extraction minus injection) rather than the total injected volume.

4.4 NATURALLY OCCURRING RADIOACTIVE MATERIALS

What are NORM

Naturally occurring radiogenic isotopes of elements such as uranium, thorium, potassium, radium and radon are collectively known as naturally occurring radioactive materials (NORM). These elements occur naturally in variable quantities in different types of bedrock and unconsolidated superficial deposits. Relatively high levels of NORM are associated with some granites, limestones, ironstones, phosphatic rocks and organic rich shales.

NORM from organic rich shales is of importance as these are also sources of shale gas. Of these, radium, which is most soluble in water and its daughter radon are considered most important as they are known to be produced during oil and gas production (e.g. Fisher, 1998). Radon has been linked to increase in risk of developing cancer of the respiratory tract (National Radiation Protection Board, 2000). The impact of radon and other NORM are considered in the following account.

NORM in organic rich shale

Uranium and thorium are the parent elements that decay to produce radium and in turn, radon. The estimated abundance of uranium in the crust is around 1.5-6.5mg/kg and thorium is about 6-20mg/kg (Plant et al., 2003). These have been shown to be particularly concentrated in organic rich shale. Jonkers et al. (1997) reported uranium in the range of 0.9-80mg/kg (mean 16.3kg/kg). A study by Harrell et al. (1991) reported between 10-40mg/kg of uranium for the Ohio shale in the USA. Ivanovich and Harman (1982) reported uranium in black shales as 1250mg/kg. The Devonian aged Marcellus Shales in the USA from which shale gas has been extracted have reported uranium concentrations of 84 mg/kg (Leventhal et al., 1981).

What is Radon

Radon is a natural radioactive gas that is invisible, has no smell or taste and can only be detected using specialist equipment. Radon is the product of the radioactive decay of radium (^{226}Ra), in turn the produced by radioactive decay of uranium (^{238}U).

Radon can occur as a gas or dissolved in water. Its major isotope is ^{222}Rn which is produced from the alpha decay of ^{226}Ra and has a half life of 3.8 days.. ^{222}Rn decays to, amongst others ^{210}Pb and ^{210}Po which have longer half lives (22.6 years and 138 days respectively) which means that these daughter isotopes can occur as films on gas processing equipment (International Association of Oil and Gas Producers, 2008).

Pathways

NORM may be returned to surface both dissolved in produced gas and groundwater and from rock returned to the surface as drill cuttings and flow-back from hydro-fracturing operations (e.g. Kraemer, 1986; White, 1992; Rowan and Kraemer, 2012).

Isotopes of radium (^{224}Ra, ^{226}Ra and ^{228}Ra) are comparatively more soluble in water compared to other NORM isotopes and their decay products, including radon (^{222}Rn), can be found in flowback and formation water. Radium has a strong adsorption with iron and manganese oxides. Radium also forms co-precipitates with $BaSO_4$, $SRCO_4$ and $CaCO_3$, complexes with chlorite, sulphate and carbonates. As a result of this co-precipitation and sorption, radium concentrations can be high in in scale deposits and sludges retained in filters or re-precipitated as scale in pipes and tanks used to handle the produced water during exploration and production (e.g. Fisher, 1998; International Atomic Energy Agency, 2003; Public Health England, 2013).

Radon (^{222}Rn) decays to, amongst others radiogenic isotopes of lead (^{210}Pb) and polonium (^{210}Po) which have longer half lives (22.6 years and 138 days respectively) and can precipitate as films on gas processing equipment (International association of Oil and Gas Producers, 2008). Radon in waste water is likely to be at its highest concentration close to its initial discharge point and its short half life means that its activity will quickly reduce in flowback waters which are stored at the surface over a period of weeks and months.

Concentrations of uranium and thorium are low in water associated with shale deposits as they are both poorly soluble in water. Uranium can accumulate in biofilms which are generated by sulphur-reducing bacteria and has been observed in seawater injection systems used in oil production (Bird et al., 2002). Concentrations of up to 370 Bq/g total uranium were observed in pipewall scrapings. Thorium, like radium, can accumulate in scale deposits.

Risk

The risk to human health relates to exposure to radiation. Exposure pathways include direct exposure to gamma radiation from scale deposits, ingestion of radioactive materials and inhalation of Radon gas (National Radiological Protection Board, 2000). Although the concentrations of NORM produced are thought to be typically below safe limits (The Royal Society And The Royal Academy Of Engineering, 2012), the likelihood for the risk to become active will be increased where Radon can accumulate in enclosed spaces (Appleton, 2000) or where waste materials become concentrated during treatment (The Royal Society And The Royal Academy Of Engineering, 2012). The main potential risk to the environment from NORM comes from contamination of surface or groundwater from unlined tanks. Public exposure to NORM is unlikely unless it is inappropriately disposed of (Public Health England, 2013).

Mitigation

Produced water containing Radium and Radon gas are likely to represent hazardous materials depending on their concentration (Radioactive Substances Act, 1993) and will be subject to regulations for handling and disposal similar to other contaminated water (Hazardous Waste (Wales) Regulations, 2005).

Exposure to radiation from scale and other materials may be mitigated for by appropriate Health and Safety measures for working with hazardous materials (Ionising Radiations Regulations, 1999) and appropriate handling and disposal of contaminated material (pipes, tanks etc.) subject to regulation (Hazardous Waste (Wales) Regulations, 2005).

Industries including conventional oil and gas, coal and potash mining, have experience of disposal of NORM in solid wastes (The Royal Society And The Royal Academy Of Engineering, 2012). Indeed the circumstance for NORM production from unconventional gas operations are likely to be very similar to those currently experienced in the oil and gas industry where radiological protection measures for workers are well documented (International Atomic Energy Agency, 2003; International Association of Oil and Gas Producers, 2008).

Scope for further research

At present there are no datasets derived from direct measurement of NORM in formation waters or source rock in potential unconventional gas horizons in Wales. This data will be critical to assess the scale and likely impact of potential NORM hazard (cf. United States Geological Survey, 1999).

Industry best practice for NORM disposal should be reviewed and tested with respect to unconventional gas operations in Wales.

4.5 OTHER ISSUES FOR CONSIDERATION IN WALES

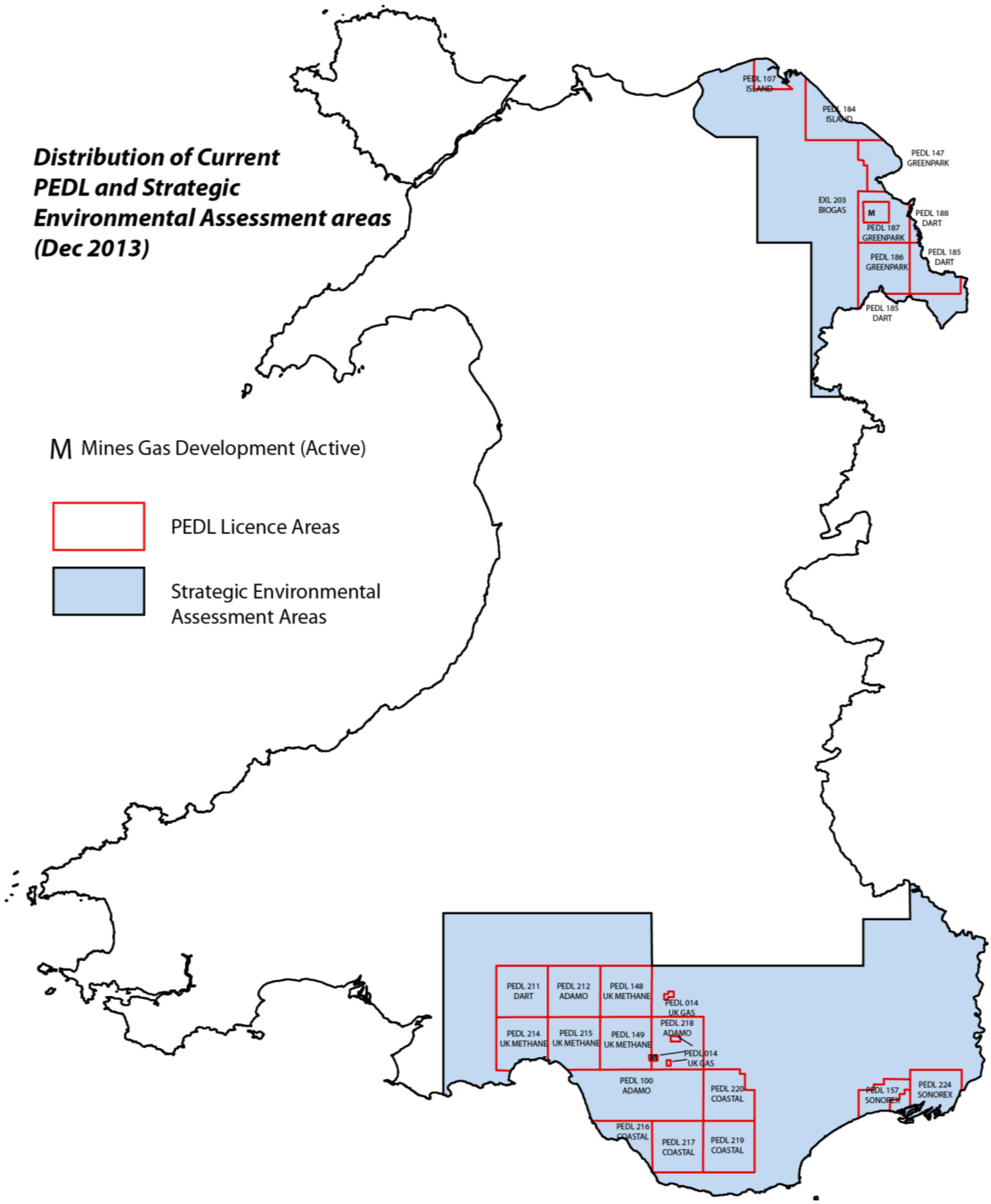
Transportation infrastructure and trafficability

Unconventional gas exploration and production is likely to require construction of new drilling pads, wells and associated infrastructure. Individual sites are likely to include storage facilities for water and proppants used for drilling, storage and/or treatment of produced water, gas processing and power supply or distribution. They will also have to be served by transport infrastructure such as roads, rail lines, pipelines, overhead or buried power lines and possibly docks (e.g. Cook et al., 2013 and references therein). Development of a shale gas play can involve the construction of a number of small sites over a large area. This is sometimes known as a fragmented development, where many individual sites make up a single project. Individual pads can contain single or multiple wells and those with multiple wells typically occupy a larger area (e.g. Cook et al., 2013 and references therein).

The short and longer-term impacts of fragmentation of sites and supporting infrastructure on the environment and communities will need to be considered to manage the environmental and social impacts associated with increased traffic. Overall design of a production development appears to have an important role to play in this.

Limited transport infrastructure, or its slow development, could delay unconventional gas developments, however there are also opportunities to utilise and improve existing infrastructure to support other local industries and communities.

Appendix 1 DECC Licensing Areas



Department of Energy and Climate Change, 2013b

Appendix 2 Resources and reserves terminology

Resource and reserves assessments require subsurface data in order to produce reliable estimates of potential volumes of hydrocarbons. The more data that is available, the more confidence can be applied to the estimate. There is not enough data available in Wales to provide a comprehensive assessment of the potential volumes of all of the potential gas, especially for shale gas.

Estimates of gas volumes involve specialist terminology which is used throughout this report. The concepts are defined here.

A gas resource estimate is the amount of gas that is estimated to be in the source rock, some of which may not be possible to extract. This is often expressed as Gas-initially-in-place (GIIP), Gas in Play (GIP) or Original Gas in-place (OGIP). GIIP estimates are typically much higher than the reserves estimates. Gas volumes expressed in this report are presented as reported by the operators who published them. The terms used are: Billions of cubic feet (bcf) and Billions of Standard Cubic Feet (bscf).

A reserves estimate defines the amount of gas that is considered possible to be produced, given appropriate technology, favourable economics and other, mainly social, factors. Reserves estimates are often expressed as a percentage and often a range of values are given in attempt to give estimates which reflect the geological uncertainty.

Reserves estimates are affected by technical uncertainty. Point data sources such as well logs, cores, reservoir properties and seismic line data for example, are extrapolated to provide 3D visualisation of the geology. Essentially, the further away from the source of data, the less confidence can be applied to it. This extrapolation process tends to introduce uncertainties which can only be overcome by the addition of more data (Demirmen, 2007).

Reserves estimates are normally given as a range of values. The range is often described qualitatively using deterministic methods or quantitatively using probabilistic methods. These methods are intended to inform a measure of uncertainty to the results.

There are two ways in which reserves estimates are typically grouped:

- As proved reserve entities from which Proved Reserves are calculated (P1)
- Cumulative basis made up of Proved (1P) plus Probably (2P) or the Proved plus the Probably plus the possible (3P)

When probabilistic methods are used, the 90% probability that the quantity quoted will equal or exceed the estimate is known as the P90. 50% probability (P50) that the quantities recovered will exceed the sum of the 2P reserves. Similarly, there will be a 10% probability (P10) that the 3P reserves will be equalled (Figure 17; Society of Petroleum Engineers, 2001).

Contingent resources are quantities of hydrocarbons estimated from known accumulations but the projects are not considered mature enough for commercial development. For contingent resources, C is used instead of P when probabilistically expressing volumes (Society of Petroleum Engineers, 2001).

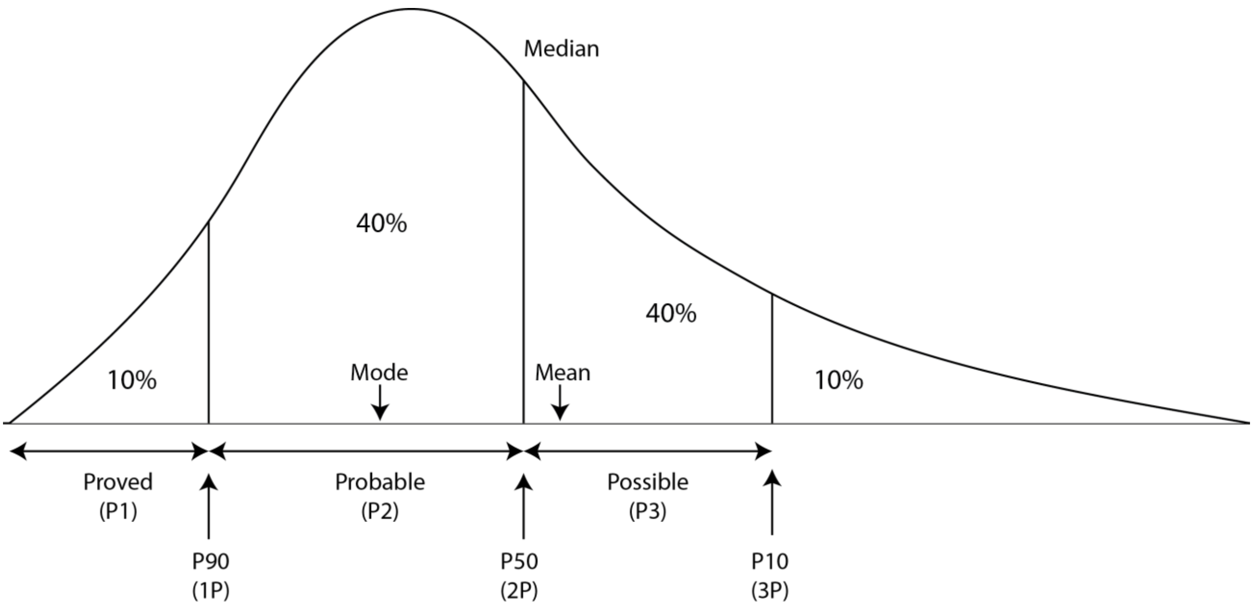


Figure 17 Definition of probabilistic reserves terminology (after Demirmen, 2007)

Recovery factors

A resource figure, expressed as GIIP is providing an estimate of a theoretical maximum volume of gas that may be present. These figures are derived by first estimating the volume of gas, within a geological unit, within an area of interest. This figure may not take into account the concept that not all of the gas will be recoverable. Jones et al., (2004) estimated that as little as 1% of the coal methane resource could be recovered. This is due to the perception that coal seams have a low permeability and low gas content as well as low resource density and planning constraints. However, in the USA, CBM developments have achieved a recovery of 30-40% in some fields. It is hoped that with the establishment of commercial CBM projects, more reliable reserves estimates can be made (Department of Energy and Climate Change, 2011b). Experience of shale gas production in the United States has shown that recovery factors of 20-30% are common but can be as low as 15% (Energy Information Administration, 2013).

Appendix 3 Favourable characteristics of shale gas plays

The classification of shale gas resources is difficult because of the large degree of variability- lateral, vertical and regionally within basins- among known shale gas plays. However, the most prospective shale gas resources discovered to date share some common geological characteristics. These characteristics described by Jarvie (2010) can be summarised as those relating to:

Chemistry:

- Marine shales which contain “type II” organic matter
- Organic rich (>1.00 wt. % present-day TOC [TOC $_{pd}$]
- 45+m of organic rich mudstone

Quantifying the amount of hydrocarbons which are present within the rock and how easily they are extracted:

- Are in the gas window (> 1.4 R_{oc})
- Low oil saturations (<5% S_o)
- Less than 100 ηd permeability
- Less that 15% porosity (typically about 4 to 7%)
- GIP values of more than 100bcf/section

Physical properties of the rocks

- Have significant silica content (>30%) with some carbonate
- Have non swelling clays
- Slightly to highly overpressured
- First year decline rates (>60%)

Factors associated with the distribution and structure of the rocks:

- Constant or known principal stress fields
- Away from structures and faults
- Continuous mapable systems.

Further detailed discussion of the importance of each of these points is given by Jarvie (2010). An understanding of these factors and how they apply to the rocks in Wales is a requirement for the development of a local shale gas industry. It is important to note that in Wales, considerable exploration and/or research is required to develop these datasets.

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