Unconventional Oil and Gas Development: Understanding and Monitoring Induced Seismic Activity

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Unconventional Oil and Gas Development: Understanding and Monitoring Induced Seismic Activity

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) commissioned by the Scottish Government to better understand the levels of induced seismic activity that could be associated with unconventional oil and gas activities in Scotland; and better understand the robust regulatory and non-regulatory actions that can be taken to mitigate any noticeable effects on communities.

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Summary

Scotland is characterised by low levels of earthquake activity. Historical observations of earthquake activity date back to the 16th century, and show that despite many accounts of earthquakes felt by people, damaging earthquakes are relatively rare. The largest recorded earthquake in Scotland had a magnitude of 5.2 ML and only two other earthquakes with a magnitude of 5.0 ML or greater have been observed in the last 400 years. As a result, the risk of damaging earthquakes is low.

Most earthquake activity in Scotland is north of the Highland Boundary Fault, on the west side of mainland Scotland, and there are fewer earthquakes in northern and eastern Scotland. It is rarely possible to associate these earthquakes with specific faults because of uncertainties both in the earthquake location estimates, which are typically several kilometres, and our limited knowledge of faulting below the surface. Earthquake activity in the Midland Valley of Scotland is lower than that north of the Highland Boundary Fault, and most of the recorded earthquakes in this area in the 1970’s, 1980’s and 1990’s were induced by coal-mining. Since the decline of the coal-mining industry in the 1990’s, very few mining-induced earthquakes have been recorded. Most of the mining induced earthquakes are small and the largest mining-induced earthquakes in Scotland had a magnitude of 2.6 ML.

Earthquake activity rates for Scotland determined from 1970 to present suggest that, on average, there are eight earthquakes with a magnitude of 2.0 or above, which is roughly the minimum magnitude felt by people, somewhere in Scotland every year. Activity rates calculated for the Midland Valley are lower, although the small number of observed earthquakes for this area means the values have large uncertainties. This suggests that earthquake hazard in the Midland Valley is lower than elsewhere in Scotland.

Existing catalogues of earthquake activity in Scotland are incomplete at magnitudes below 2 ML, from 1970 to present, and for higher magnitudes prior to this. This is due to the detection capability of the networks of seismometers that have operated in the study area over the last few decades. This, together with the low background activity rates, limits our ability to identify any areas that might present an elevated seismic hazard for any Unconventional Oil and Gas (UOG) operations based on seismic data alone. Similarly, limited information about the state of stress in the Earth’s Crust means that it is not possible to identify any particular parts of the study area where faults are more likely to be reactivated and that may present an elevated seismic hazard for any UOG operations.

The process of hydraulic fracturing in order to increase the permeability of reservoir formations and stimulate the recovery of hydrocarbons is generally accompanied by microseismicity, commonly defined as earthquakes with magnitudes of less than 2.0 that are too small to be felt. In the US and Canada, the large number of hydraulic fracturing operations that have been carried out and the small number of felt earthquakes directly linked to these operations, suggests that the probability of felt earthquakes caused by hydraulic fracturing for recovery of hydrocarbons is very small. Over 1.8 million hydraulic fracturing operations have been carried out in the US in ~1 million wells and there are only three documented cases of induced earthquakes conclusively linked to hydraulic fracturing for shale gas recovery. The largest of these earthquakes had a magnitude of 3.0. However, in western Canada, increases in the annual numbers of earthquakes over the last ten years correspond to increases in the number of hydraulically fractured wells, suggesting that hydraulic fracturing has induced earthquakes. There are also a number of documented examples of earthquakes with magnitudes larger than 3 in Canada that have been linked to hydraulic fracturing for shale gas recovery. The largest of these was a magnitude 4.4 earthquake, which is the largest known earthquake suspected to have been triggered by hydraulic fracture operations in a hydrocarbon field anywhere in the world. However, as in the US, the
probability of induced earthquakes that can be felt appears small given the large number of hydraulically fractured wells (>12,000).

Studies of earthquake activity in the Raton Basin (United States), an area that has produced coal-bed methane since 1994, suggest that this activity is related to the subsequent disposal of wastewater from the coal-bed methane extraction process by injection into deep wells, rather than from the extraction process itself. Literature was not located concerning induced seismicity and coal-bed methane extraction in Canada, Australia or other parts of the USA, suggesting that this is not a major issue in those areas.

Recent increases in earthquake rates and significant earthquakes in many areas of the Central and Eastern United States have been linked to the disposal of wastewater by injection in to deep wells rather than hydraulic fracturing, and provide a considerable body of evidence that this activity has a non-negligible contribution to the seismic hazard. Seismic hazard forecasts for the Central and Eastern United States now include contributions from both induced and natural earthquakes and show increases in earthquake hazard by a factor of 3 or more in some areas of induced earthquake activity. However, although many wastewater injection wells can be associated with earthquakes, the majority are not. Additionally, the nature of the wastewater injected into deep wells varies: while some comes from hydraulic fracturing used in unconventional oil and gas production, many wastewater injection wells are used to dispose of produced water from conventional hydrocarbon production.

Although the triggering process of natural and induced earthquakes may differ, there is no evidence to suggest that the expected maximum magnitude will not be similar.

The UK Department for Energy and Climate Change (DECC, 2013) published a regulatory roadmap that outlines regulations for onshore oil and gas (shale gas) exploration in the UK. These regulations contain specific measures for the mitigation of induced seismicity including: avoiding faults during hydraulic fracturing; assessing baseline levels of earthquake activity; monitoring seismic activity during and after fracturing; and, using a ‘traffic light’ system that controls whether injection can proceed or not, based on that seismic activity. Regulatory measures to mitigate the risk of induced seismicity are also in place in the US and Canada. In the US, much of this regulation is aimed at induced seismicity related to wastewater disposal in deep wells, although this is also relevant to induced seismicity from hydraulic fracturing. These measures are broadly similar to those specified by DECC.

In the UK, the magnitude limit for the cessation of hydraulic fracturing operations (0.5 ML) is considerably less than the limits in California (2.7 ML) and Illinois, Alberta and British Columbia (4.0 ML), and may be considered a conservative threshold. Local monitoring systems that are capable of reliable measurement of earthquakes with very small magnitudes will be required to implement the UK limit successfully. A magnitude 4.0 ML earthquake in an area of high population density, such as the Midland Valley of Scotland, would be strongly felt by many people and may even cause some superficial damage.

British Standards BS 6472-2 and BS 7385-2 define limits for acceptable levels of ground vibrations caused by blasting and quarrying and the limits for vibrations caused by blasting, above which cosmetic damage could take place. A comparison of modelled ground motions for a range of earthquake magnitudes with these limits suggests that earthquakes with magnitudes of 3.0 or less are unlikely to exceed the limits above which cosmetic damage may occur, as set out in BS 7385-2, except at distances of less than a few kilometres. Smaller earthquakes may also exceed the limits for vibration set out in BS 6472-2, but again only at small distances of less than a few kilometres.

Improved understanding of the hazard from induced earthquakes and the successful implementation of regulatory measures to mitigate the risk of induced seismicity are likely to require additional data from a number of sources:
(1) Higher quality earthquake catalogues that can be used to determine reliable estimates of background activity rates and that allow the discrimination and forecasting of induced seismic activity. Without these, any changes in the rate of small magnitude events may be obscured by the uncertainties. This will require denser arrays of seismic instrumentation than at present. These dense arrays are also required to provide high-quality, real-time earthquake locations, which are required as part of any traffic light system for mitigating risk. It is important that the data from any such arrays are openly available to maintain public confidence.

(2) Geological and geophysical data that can be used to map sub-surface fault systems in high resolution, measure the orientation and magnitude of the stress field, and determine the hydrological properties of the sub-surface.

(3) Industrial data from hydraulic fracturing operations such as injection rates and volumes, along with downhole pressures.
1 Introduction

A recent study by the British Geological Survey (Monaghan, 2014) stated that the significant volumes of potentially productive shale in the Midland Valley of Scotland represent a considerable oil and gas resource. In the Smith Commission Report of November 2014 for the further devolution of powers to the Scottish Government, the licensing of onshore oil and gas extraction for Scotland is to be devolved to the Scottish Government together with the mineral access rights for underground onshore extraction of oil and gas. In January 2015, the Scottish Government announced a moratorium on onshore oil and gas in Scotland and has adopted a cautious, considered and evidence based policy to unconventional oil and gas in Scotland. The aims of this project are to: (1) better understand the levels of induced seismic activity that could be associated with unconventional oil and gas activities in Scotland; and (2) better understand the robust regulatory and non-regulatory actions that can be taken to mitigate any noticeable effects on communities.

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. Davies et al. (2013) present a review of published examples of earthquakes induced by a variety of activities: underground mining, deep artificial water reservoirs, oil and gas extraction, geothermal power generation and waste disposal have all resulted in cases of induced seismicity. Furthermore, there are numerous examples of induced earthquakes in hydrocarbon fields related to oil and gas production (e.g. Suckale, 2010). These are often a response to long-term production, where the extraction related subsidence is compensated by, for example, normal faulting on existing faults near or inside the reservoir (Van Eijs et al., 2006). For example, in 2001 a magnitude 4.1 Mw earthquake occurred in the Ekofisk field in the central North Sea (Ottomoller et al., 2005). The earthquake was thought to be related to the injection of around 1.9x10^6 m^3 of water.

Induced earthquakes with magnitudes as large as 3.5-4.0 ML are well documented in Enhanced Geothermal Systems (EGS) (e.g. Majer et al., 2007), in which injected fluids are heated by circulation through a hot fractured region of crystalline rocks and then brought back to the surface for power generation. Such crystalline rocks have different mechanical properties to sedimentary rocks, such as shales which may make induced seismicity associated with EGS more likely. There are examples of EGS in North America (Geyser, California), Central America (Berlin, El Salvador), Europe (Soulta, France; Basel, Switzerland; Rosemanowes, Cornwall) and Australia (Cooper Basin). Earthquakes with magnitudes of up to 4.6 and 4.4 ML have observed at Geyser and Berlin. The largest earthquakes observed at Soulta and Rosemanowes had magnitudes of 2.7 and 2.1 ML. A series of magnitude 3+ earthquakes induced during an EGS project in Basel, Switzerland resulted in the suspension of the project, which was ultimately abandoned almost 3 years later following further study and risk evaluation after these seismic events (Giardini, 2009).

In addition, several of the largest earthquakes in the U.S. midcontinent in 2011 and 2012 may have been triggered by nearby disposal wells (e.g. Horton, 2012; Kim, 2013), suggesting that wastewater disposal by injection in to deep wells poses a significant seismic risk. The largest of these was a magnitude 5.7 event in central Oklahoma that destroyed 14 homes and injured two people (Kerenan et al., 2013).
The process of hydraulic fracturing in order to increase the permeability of reservoir formations and stimulate the recovery of hydrocarbons is also generally accompanied by microseismicity, commonly defined as earthquakes with magnitudes of less than 2.0 that are too small to be felt. Induced seismicity during hydraulic fracture operations has been discussed by a number of authors in the last few years, including Shetema et al. (2012), Warpinski et al. (2012) and Ellsworth (2013). A report by the National Research Council in the U.S. (NAS, 2012) concluded that the process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk of inducing felt seismic events. Similarly, a Royal Society and Royal Academy of Engineering report in the UK (2012) concluded that “the health, safety and environmental risks associated with hydraulic fracturing (often termed ‘fracking’) as a means to extract shale gas can be managed effectively in the UK as long as operational best practices are implemented and enforced through regulation.” However, more recently, there have also been a number of documented examples of rather larger felt earthquakes induced during hydraulic fracturing operations. These include: Horn River, Canada, 2009-2011 (BC Oil and Gas Commission, 2012); Blackpool, UK, 2011 (de Pater and Baisch, 2011); Garvin County, Oklahoma, 2011 (Holland, 2013); Montney, Canada, 2014-2014 (BC Oil and Gas Commission, 2014); Crooked Lake, Alberta, Canada, 2013-2014 (Schultz, 2015). The largest event had a magnitude of 4.4 Mw, which is, to date, the largest known earthquake suspected to have been induced by hydraulic fracturing in a hydrocarbon field anywhere in the world.

In this study we have addressed five specific research questions:

1. What are the characteristics of Scottish geology in areas assessed by the British Geological Survey for their prospectivity for shale oil and gas and CBM, with a focus on the characteristics most relevant to the different stages and techniques used in unconventional oil and gas developments?
2. What is the international and UK experience of induced seismic activity arising from hydraulic fracturing with an emphasis on sites with similar geological characteristics to Scotland?
3. What are the international experiences and lessons from statutory and non-statutory frameworks for monitoring and mitigating induced seismic activity from unconventional oil and gas developments, and from other applicable industries such as onshore oil exploration and quarrying?
4. What are the main international lessons and experiences from seismic monitoring and mitigation at unconventional oil and gas development sites? What does best practice look like and how relevant is the Scottish Government’s existing planning advice on controlling blasting at quarries to unconventional oil and gas developments?
5. What lessons are there from the research as a whole in relation to monitoring and regulating induced seismic activity arising from unconventional oil and gas developments, including consideration of the DECC ‘traffic light system’ and the requirement for an associated Hydraulic Fracturing Plan, which currently applies across the UK? How could these lessons be interpreted and applied in a Scottish context to support robust regulation and industry best practice?

Each question is addressed in separate section of the report.

In Section 2 we review the geological and seismic characteristics of the Midland Valley of Scotland. This includes a description of key features of the prospective Carboniferous strata in the study region such as the timing and style of pre-existing faulting. Catalogues of natural and man-made seismicity are used to examine the spatial and temporal characteristics of earthquake activity in the study area and establish robust estimates of earthquake activity...
rates that represent a numerical expression of the expected future seismicity of the region. Mining-induced earthquakes are removed from the catalogue using a spatial filter to ensure that our estimates of earthquake activity rate are not contaminated by induced seismicity. Published earthquake focal mechanisms along with smoothed stress orientations are used to evaluate the current state of crustal stress in the study area. The resulting estimates of stress direction are compared with orientation of known faults to estimate fault reactivation potential and highlight those fault that may present an elevated seismic hazard for any UOG operations.

In section 3 we present a review of induced seismicity in UOG operations. Limited data is available globally, and we focus on three geographic areas: central and eastern United States; the West Canada Sedimentary Basin; and Blackpool, UK. We also examine seismicity in the Raton Basin, an active coal-bed methane field in the Colorado-New Mexico border region, known for several notable earthquakes, including a magnitude 5.3 event in August 2011. Given the limited data available, we also discuss examples of recent seismicity related to waste water disposal in the eastern United States.

Section 4 provides a detailed overview of the regulatory frameworks that are in place in both Europe and North America for monitoring and mitigating induced seismic activity from unconventional oil and gas developments. We compare the regulatory framework to address possible seismic activity associated with future UOG operations that is in place in the UK with those that are in place in the USA and Canada. We also draw on experience of monitoring induced seismic activity in Enhanced Geothermal Systems (EGS), which has led to the development of “traffic light systems” linked to real-time monitoring of seismic activity.

In section 5 we discuss some of the lessons that can be learned from previous experiences of seismic monitoring and mitigation of induced seismicity in UOG operations. Examples are used to highlight some of the problems that may result from lack of monitoring before, during and after operations. We also examine the detection capability of existing seismic monitoring networks in the study area. We use a stochastic modelling approach to simulate possible ground motions for small to moderate earthquakes that might be related to activities such as hydraulic fracturing and compare these with the limits for levels of ground vibrations caused by blasting set out in the British Standards BS 6472-2 and BS 7385-2.

In section 6 we review some of the key lessons that can be learned from the research.
2 Geological and Seismic Characteristics of the Study Area

2.1 OVERVIEW
The bedrock geology of the Midland Valley of Scotland consists mostly of sedimentary rocks, rich in resources such as coal, limestone, ironstone and shale, which have been extracted throughout the years using underground or surface mining techniques. These rocks were formed between 350 and 300 million years ago, during a time when swamps flourished in a warm humid climate, when Mississippi sized river systems deposited vast quantities of sediments, and sea level fluctuations periodically flooded the land. Over geological time, these sediments were turned to rock and following numerous plate tectonic events, buried at depths sufficient to generate hydrocarbons. Such tectonic forces also deformed the rocks, forming geological folds, faults and fractures within the strata. These structures are mapped across the Central Belt of Scotland at all scales, and fall into three trends: E-W, ENE-WSW and NW-SE.

An analysis of recent instrumental recordings of earthquakes and older historical data confirms that earthquake activity in Scotland is low. On average there are eight earthquakes with a magnitude of 2.0 ML or above, somewhere in Scotland every year. The largest recorded earthquake in Scotland had a magnitude of 5.2 ML and only two other earthquakes with magnitudes of 5.0 ML or greater have been observed in the last 400 years. As a result, the risk of damaging earthquakes is low. Most of this earthquake activity is north of the Highland Boundary Fault, on the west side of mainland Scotland. Earthquake activity in the Midland Valley of Scotland is lower, and most of the recorded earthquakes in this area were induced by coal-mining. Since the decline of the coal-mining industry in the 1990’s, very few mining-induced earthquakes have been recorded. Existing catalogues of earthquake activity in Scotland are incomplete at magnitudes below 2 ML from 1970 to present, and for higher magnitudes prior to this. This limits our ability to identify any areas that might present an elevated seismic hazard for any UOG operations. Similarly, limited information about the state of stress in the Earth’s Crust mean that it is not possible to identify any particular parts of the study area where faults are more likely to be reactivated and that may present an elevated seismic hazard for any UOG operations.

2.2 BACKGROUND
The UK is characterised by low levels of earthquake activity and low seismic hazard, in keeping with its intraplate setting. Historical observations of earthquake activity date back to the 14th Century, and show that despite many accounts of earthquakes felt by people, damaging earthquakes are relatively rare (Musson, 2007). This earthquake activity is caused by reactivation of existing faults by tectonic stresses from the ongoing collision of the African and Eurasian tectonic plates and widening of the Atlantic Ocean along the Mid-Atlantic ridge, and stresses from isostatic readjustment due to previous episodes of ice loading. The largest recorded earthquake had a magnitude of 5.9 Mw and there have been sixteen earthquakes with magnitudes of 5.0 Mw or greater since 1650. An analysis of recurrence statistics suggests that an earthquake with a magnitude of 5 Mw or above occurs somewhere in the British Isles on average every 50 years, while an earthquake with a magnitude of 6.0 Mw or above occurs roughly every 500 years. Most earthquakes in the British Isles nucleate in the mid-Crust at depths of 5-15 km, and there is some evidence to
suggest that the largest earthquakes nucleate at the greater depths in the Crust. By contrast, there is no evidence of any earthquake in the last five hundred years that has ruptured the surface, although earthquakes with magnitudes close to the expected maximum magnitude (~6.5 Mw) for the British Isles and which nucleate at depths of less than 10 km, may, in theory, be capable of producing ruptures that propagate close to the surface.

<table>
<thead>
<tr>
<th>WHAT IS AN EARTHQUAKE?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquakes are the result of sudden movement along faults within the Earth that releases stored up strain in the form of seismic waves or vibrations that travel through the Earth and cause the ground surface to shake. Such movement on the faults is generally a response to long term deformation and build-up of stress, caused by processes such as plate tectonics. When this stress exceeds the friction that holds the rocks on either side of the fault together, they slide or slip past each other. The size of any earthquake depends on both the area of the fault that ruptures and also the average amount of slip or displacement on the rupture plane. Larger rupture areas and larger displacement lead to larger earthquakes. The largest earthquakes occur on ruptures that are many hundreds of kilometres long, with areas of several thousand square kilometres, and that have displacements of many metres. Earthquake activity is greatest at the boundaries between the Earth’s tectonic plates, where the differential movement of the plates results in repeated accumulation and release of strain. These include the edges of the Pacific and other subduction zones, e.g. the Mediterranean Trench between Africa and Eurasia or collision zones, e.g. the Himalayan Belt. These are commonly referred to as interplate earthquakes. However, earthquakes can also occur within the plates far from the plate boundaries, and where strain rates are low. These are often referred to as intraplate earthquakes. Large areas of Asia, Australia, Europe and North America all experience intraplate earthquakes, although these events are relatively rare.</td>
</tr>
</tbody>
</table>

2.3 GEOGRAPHIC AND TECTONIC CONTEXT

The UK lies on the northwest part of the Eurasian plate and at the northeast margin of the North Atlantic Ocean (Figure 2.1). The nearest plate boundary lies approximately 1,500 km to the northwest where the formation of new oceanic crust at the Mid-Atlantic ridge has resulted in a divergent plate boundary and significant earthquake activity. Around 2,000 km south, the collision between Africa and Eurasia has resulted in a diffuse plate boundary with intense earthquake activity throughout Greece, Italy and, to a lesser extent, North Africa. This activity extends North through Italy and Greece and into the Alps. The deformation arising from the collision between the African and European plates results in compression, commonly referred to as “Alpine compression”, that is generally directed in a north-south direction. The northeast margin of the North Atlantic Ocean is passive and is characterised by low levels of seismic activity in comparison to other passive margins around the world.

As a result of this geographic position, the UK is characterised by low levels of earthquake activity and low seismic hazard. Evidence for this comes from observations of earthquake activity dating back to the 14th Century, which suggests that although there are many accounts of earthquakes felt by people, damaging earthquakes are rare.

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

Figure 2.1. Black circles show the distribution of earthquakes with a magnitude of greater than 5 across Europe. The red line shows the margins of the Eurasian plate. The great majority of earthquake activity is located at the southern margin in Greece and Italy along the collision zone between Africa and Eurasia. The inset shows the distribution of earthquakes in North America. Plate boundary data from Bird (2003). Earthquake Data from the British Geological Survey World Seismicity Database, © NERC 2016

2.4 GEOLOGY AND FAULTING OF THE MIDLAND VALLEY OF SCOTLAND

2.4.1 What unconventional oil and gas resources are being considered in Scotland and are relevant to this project?

A range of unconventional oil and gas (UOG) resources have been assessed in Scotland, including shale oil and shale gas in Carboniferous shales in the Midland Valley of Scotland (Monaghan, 2014), and coal mine methane, abandoned mine methane, coal bed methane and underground coal gasification in coal seams and associated mines in Central Scotland, the Sanquhar and Canonbie coal fields (Jones et. al., 2004). In this report we focus on the shale
oil, shale gas and coal bed methane UOG resources. The majority of shale- and coal-bearing strata lie in the geological terrane of the Midland Valley of Scotland (essentially occupying the same geographical area as the Central Belt of Scotland), situated between the Scottish Highlands to the north and the Southern Uplands to the south. These strata are distributed in the west of Scotland in Ayrshire, and Douglas, and through central Scotland (including Clackmannanshire, North Lanarkshire, Stirlingshire) and eastwards to Fife and the Lothians (Figure 2.2).

Shale oil and shale gas are produced from an organic-rich rock known generically as ‘shale’, but more precisely termed mudstone, carbonaceous mudstone, oil-shale and fine siltstone. Shale is a sedimentary rock, composed of fine-grained (clay and silt sized) particles and which may contain organic matter (e.g. derived from land and aquatic plants, bacteria and animal remains). Shale is typically considered as the source rock in conventional oil and gas accumulations: however, with unconventional hydrocarbon accumulations, shale acts as both source and reservoir rock, with hydrocarbons extracted using hydraulic fracturing techniques.

Coal bed methane (CBM) is produced from a sedimentary rock known as coal. Coal is formed from organic matter (e.g. prehistoric vegetation accumulated in swamps and peat bogs), and as a result contains a high proportion of carbon and consists largely of organic carbonaceous molecules. Coal seams in Scotland typically contain one or more sets of sub-parallel near-vertical fractures known as cleats.

2.4.2 What is the geology and characteristics of that geology in the Midland Valley of Scotland?

Coincident with the geographically low-lying limits of the Central Belt is the geological terrane of the Midland Valley of Scotland, a fault-bounded Late Palaeozoic sedimentary basin. It is composed of an internally structurally complex arrangement of Devonian, Carboniferous and Permian sedimentary and volcanic rocks, with up to over 5,500 m of Carboniferous strata locally (Cameron and Stephenson, 1985; Read et al., 1996).

Potentially prospective Carboniferous shales and coal beds are buried beneath an area from Glasgow to Edinburgh (Figure 2.3), to the Lothians, Falkirk, Clackmannan and Fife, and extending into Ayrshire and Lanarkshire (Monaghan, 2014 and Jones et al., 2004). These prospective resources belong to a total of eleven Carboniferous stratigraphic units, in descending stratigraphical order: the Coal Measures Group, Passage Formation, Upper Limestone Formation, Limestone Coal Formation, Lower Limestone Formation, Pathhead Formation, Sandy Craig Formation, Pittenweem Formation, West Lothian Oil Shale Formations, Anstruther Formation and the Gullane Formation. The units containing shale and coal prospective resources are summarised in Table 2.1. The units are distinguished based on their age and lithological composition (e.g. variations in the amount of mudstone, sandstone, limestone etc).

The Coal Measures Group are the uppermost stratigraphic unit of interest for potential UOG resources in the Central Belt of Scotland. Where the Coal Measures Group are not present at surface, they have been eroded away and therefore do not overlie any other Formation (Figure 2.4). The same rule applies to all stratigraphic units beneath the Coal Measures Group. Therefore, where any Formation is present at surface, it will be underlain by units stratigraphically beneath them, unless that unit is not present (due to non-deposition in that area during the Carboniferous) or unless the stratigraphy is interrupted by faulting.
Figure 2.2: Geology of the Midland Valley of Scotland from 1:625 000 scale DigMap BGS©NERC. Potentially prospective units are shown.
Figure 2.3. (b) Extents of potential coal bed methane resource from Jones et al. (2004). (c) Extents of potential shale gas and shale oil resource from Monaghan (2014).
<table>
<thead>
<tr>
<th>Age</th>
<th>Group</th>
<th>Glasgow, Lanarkshire, Ayrshire</th>
<th>West Lothian</th>
<th>East Lothian</th>
<th>Fife</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westphalian</td>
<td>Scottish Coal Measures Group</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(c. 317 Ma)</td>
<td>Scottish Upper Coal Measures Formation</td>
<td>Cyclical sandstone, siltstone, mudstone with minor coal, &gt;1200 m</td>
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<tr>
<td></td>
<td>Scottish Middle Coal Measures Formation</td>
<td>Cyclical sandstone, siltstone, mudstone, seatrock and coal, 350 m</td>
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<tr>
<td></td>
<td>Scottish Lower Coal Measures Formation</td>
<td>Cyclical sandstone, siltstone, mudstone, seatrock and coal, 240 m</td>
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<tr>
<td>Namurian</td>
<td>Clackmannan Group</td>
<td></td>
<td></td>
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<tr>
<td>(c. 330 Ma)</td>
<td>Passage Formation</td>
<td>Sandstone, conglomerate and claystone with minor coal, limestone and ironstone, 380 m</td>
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<td></td>
<td>Upper Limestone Formation</td>
<td>Cyclical limestone, mudstone, siltstone and sandstone, seatrock and coal, &gt;600 m</td>
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<tr>
<td></td>
<td>Limestone Coal Formation</td>
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<td></td>
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<tr>
<td></td>
<td>Lower Limestone Formation</td>
<td>Cyclical limestone, mudstone, siltstone and sandstone with minor seatrock and coal, 240 m</td>
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<tr>
<td>Visean</td>
<td>Strathclyde Group</td>
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<tr>
<td>(c. 346 Ma)</td>
<td>Lawmuir Formation</td>
<td>West Lothian Oil-Shale Formation</td>
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<td></td>
<td>Kirkwood Formation</td>
<td>Cyclical oil-shale, sandstone, siltstone and mudstone with minor coal, limestone, dolostone and ironstone, &gt;1120 m</td>
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<td></td>
<td>Clydeside Plateau Volcanic Formation</td>
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<td></td>
<td>Gullane Formation</td>
<td>Cyclical sandstone, mudstone and siltstone with minor coal, seatrock, limestone, dolostone and ironstone, 560 m</td>
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<tr>
<td></td>
<td>Anstruther Formation</td>
<td>Mudstone, siltstone and sandstone with minor limestone, dolostone, oil-shale and coal, &gt;810m</td>
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<tr>
<td></td>
<td>Arthur’s Seat and Garleton Hills Formation</td>
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<td></td>
<td>Pathhead Formation</td>
<td>Mudstone and siltstone with limestone and dolostone and minor sandstone, coal and ironstone, 220m</td>
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<td></td>
<td>Sandy Craig Formation</td>
<td>Mudstone and siltstone with minor oil-shale, limestone, sandstone and coal, 670m</td>
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<tr>
<td></td>
<td>Pittenweem Formation</td>
<td>Mudstone and siltstone with minor limestone, oil-shale and sandstone, 260 m</td>
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<tr>
<td></td>
<td>Charles Hill Volcanic Member</td>
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<td></td>
<td>Fife Ness Formation</td>
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</table>

Table 2.1. Summary of the Carboniferous stratigraphy of the Midland Valley of Scotland (modified after Browne et al. 1999 and Monaghan 2014; dates from Waters, 2011). The eleven potentially prospective intervals are colour shaded blue for coal-rich interval, green for shale-rich interval and yellow for combined shale- and coal-rich interval. Note that the coal-rich intervals highlighted blue also contain shale but were excluded from the shale resource assessment of Monaghan (2014) due to their current day burial depth largely being < 1 km.
Figure 2.4. Schematic cartoon illustrating relationship between erosion, surface exposure and strata at depth. Cartoon not to scale. The equivalence of the stratigraphic groups shown to component coal and shale-bearing formations is listed in Table 1.

In Ayrshire, and the Sanquhar and Douglas Coalfields, in areas where the Coal Measures Group are present at surface, all potentially prospective stratigraphic units are present either at surface or at depth down to the Lower Limestone Formation (Figure 2.2). The West Lothian Oil Shale, Gullane and Anstruther formations are not present at depth in this location. Throughout the remainder of the Central Belt, to the east of the mapped Clyde Plateau Volcanic Formation, potentially prospective stratigraphic units are present either at surface or at depth down to the Gullane, Anstruther or West Lothian Oil Shale formations, where the Coal Measures Group are present at surface (Figure 2.2). The West Lothian Oil Shale Formation and lateral equivalents crops out in West Lothian and is interpreted in boreholes to the north-west and west at depths of up to 5100 m (Monaghan, 2014). The Anstruther and Gullane formations are present throughout the eastern part of the region at depths of up to 5800 m. The West Lothian, Gullane and Anstruther formations are not overlain by any other Formation where they crop out at surface between Edinburgh and Linlithgow, and in the north-east of Fife and in East Lothian.

All formations described above are intruded (in varying volumes and intensities) by Palaeozoic and Palaeogene aged igneous sills and dykes.

2.4.3 What particular character of these formations are relevant to unconventional development, in particular induced seismicity?

Each stratigraphic unit defined in Table 2.1 has its own unique lithological (rock type) character (e.g. amount of sandstone, coal, mudstone). Different rock types have different strengths and mechanical properties which are likely to vary with pressure, depth and temperature. This affects the way in which they fail as a result of stress or deformation. For example, limestones and sandstones are mechanically strong rocks composed of cemented grains and interlocking crystals, which at high levels in the crust, would tend to deform in a brittle fashion (i.e. tensional failure by formation of natural fractures) when deformed (Figure 2.5). Shales and mudstones are mechanically weaker rocks, composed predominantly of organic material and clay, and therefore tend to deform in a more ‘ductile’ fashion (i.e. slip occurs along bedding planes as well as fracturing the rock mass) when deformed (Figure 2.6). When these rock types form a layered succession (e.g. such as in the Limestone Coal Formation), they behave and respond accordingly to their lithology. When studied at surface, the dense fractured nature of shale and bedding parallel slip is not observed or repeated in an overlying strong limestone for example, just as the widely spaced natural fractured nature of a limestone is not repeated in the underlying shale.
As a general rule, the formations are dominated by the following lithologies (Cameron and Stephenson 1985, Midland Valley Memoir):

<table>
<thead>
<tr>
<th>Formation Name</th>
<th>Dominant Lithologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gullane and Anstruther</td>
<td>Sandstone and shale</td>
</tr>
<tr>
<td>West Lothian Oil Shale</td>
<td>Mudstone, oil-shale, siltstone</td>
</tr>
<tr>
<td>Lower Limestone Formation</td>
<td>Limestone, mudstone, sandstone</td>
</tr>
<tr>
<td>Limestone Coal Formation</td>
<td>Sandstone, siltstone, mudstone, coal</td>
</tr>
<tr>
<td>Upper Limestone Formation</td>
<td>Limestone, sandstone, mudstone</td>
</tr>
<tr>
<td>Passage Formation</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Coal Measures Group</td>
<td>Sandstone, siltstone, mudstone, coal</td>
</tr>
</tbody>
</table>

Limited published datasets are available on rock properties, such as mechanical strength and behaviour, in the Carboniferous rocks considered as UOG resources in Scotland. Engineering geology borehole datasets from site investigation reports provide one data source for relatively shallow cored strata (commonly less than 100 m drilled depth). A brief overview of data held in the BGS geotechnical database suggest the uniaxial compressive strength varies between 3.4 (weak) to 195 MPa (very strong) in the Clackmannan Group (Upper Limestone, Limestone Coal and Lower Limestone formations) and fracture index\(^1\) in the Coal Measures and Limestone Coal Formation strata varies from 0-200. Figure 2.7 and Figure 2.8 demonstrate the variability within some of the measured and described rock properties. This dataset requires further specialist interpretation as to whether it is likely to be applicable in the deep subsurface and how it varies with lithology.

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\(^1\) The fracture index is an engineering geology classification of a count of the number of fractures over an arbitrary length of core of similar intensity of fracturing. It is usually expressed as fractures per metre).
Figure 2.7: Percentage of described strength from borehole core for six stratigraphic units from engineering geology descriptions in site investigations from the Glasgow area. Image courtesy David Entwisle, BGS.

Figure 2.8: Box and whisker plot of measured uniaxial compressive strength of different lithologies from Carboniferous strata described in engineering geology site investigations from the Glasgow area (note engineering geology classes 1.25-5=weak, 5-12.5=moderately weak, 12.5-50=moderately strong, 50-100 strong, 100-200=very strong). Image courtesy David Entwisle, BGS.
Some description of eastern Scotland rock mechanical properties are given in Olden et al (2014) though this study considered the behaviour of rocks buried more deeply than the units of interest for UOG and modelled subject to injection of large volumes of CO$_2$.

Other indicators of in-situ stress orientation, of drilling induced tensile fractures and of variation with lithology in the heterolithic succession could be investigated by examining borehole/well breakouts, as in Kingdon et al. (2016a, b), Williams et al. (2015). However no such study is currently known from Scotland. The age and quality of well datasets, along with their spatial distribution could limit work of this type.

There are also limited datasets available on baseline levels of natural fracturing within Carboniferous strata. For example, cleat, a network of orthogonal extensional joints, is a characteristic structure in coals. Cleat azimuths form perpendicular to the minimum principal stress and parallel to the maximum horizontal stress during fracture formation (Rippon et al., 2006). Cleat data are necessary for modelling bulk rock strength behaviour for coal gasification technology and for optimum in-seam drilling directions in coalbed methane exploitation (Gayer & Harris, 1996 & Kent 1996). In general, the main cleat azimuth will vary near faults and the cleat will increase in frequency as will associated mineralisation. Fox (1965) noted cleat frequency was greater in bright coals than in durain or cannel coals. The main cleat azimuths in the Lothians and Fife are broadly NW-SE, with a range from 287° to 328° in the Lothians, and in Fife from 285° to 335° (Fox, 1965: Rippon et al., 2006). The main cleat in coals of the Clackmannan area has an E-W trend (parallel to the prominent normal fault set).

Baseline levels of natural fracturing will change across the area depending on local tectonic background, proximity to faulting, fold structure and bed thickness. The presence of igneous dykes or sills (mechanically strong and crystalline rocks) will likely have a local effect on rock strength and deformation characteristics.

In addition to natural fracturing and bedding planes between sedimentary units, the formations are also affected by other discontinuities including faulting and mine workings. Much of the Central Belt is undermined where coal-bearing strata are present (see Jones, 2004; Gillespie et al., 2013), leaving voids, collapsed workings or packed waste in the sub-surface space previously occupied by the coal. In mines that underwent ‘stoop and room’ (where pillars of rock are left unmined to support the mine roof), mining voids can be 50% (Gillespie et al., 2013). In ‘longwall’ mines (where the coal seam is worked between two parallel access roadways and the roof is allowed to collapse as the workings advance), only 20% of voids may remain (Younger and Adams, 1999 in Gillespie et al., 2013). An increase in fractures associated with rock collapse and changes in rock stress is likely in the strata above the mines in a zone of extraction-related subsidence (Younger and Adams, 1999). The presence and extent of mine workings should therefore be factored into detailed studies on UOG potential. Detailed mine plans of the workings can also be used to gain a more detailed knowledge of faulting at the local scale.

### 2.4.4  What is the geological structure of the area?

The Midland Valley of Scotland, a series of ancient rift basins, is bounded in the north by the Highland Boundary Fault and in the south by the Southern Upland Fault, both ENE-WSW trending structures. The graben structure was developed in the early Devonian (Bluck, 1978) in a zone of crustal weakness inherited from the Lower Palaeozoic (during the Caledonian Orogeny). The area underwent extensive tectonic deformation over the Palaeozoic Era, forming a series of inter-related depocentres and intra-basinal highs. There is little direct tectonic evidence for any subsequent major tectonic event affecting the area (Underhill et al., 2009). The faults within the Central Belt are generally normal (e.g. East Ochil Fault) or oblique-slip structures (i.e. some component of strike-slip movement, e.g. Paisley Ruck), with occasional instances of reverse slip (e.g. Pentland Fault). They are typically steeply dipping structures e.g. between 50 and 85 (near-vertical) degrees (Monaghan 2013), although low angle thrust faults of approximately 30 degrees in dip have been identified in surface coal mines during field visits by the BGS. Fault dips can be
Faults are typically drawn on BGS maps as linear planar structures. However, in nature faults are not simple linear structures but comprise a zone of intensely variably fractured, broken rock (e.g. Caine et al., 1996). Fault zone complexity is dependent on a number of properties including: host rock lithology, displacement and pre-existing structure in the rock mass. A single fault may change in complexity, structure, strike and dip along its length (e.g. Childs et al. 1997; Schulz and Evans 1998; Wibberley et al., 2008). Subsidiary faults are often found within the fault zone of large fault structures, although their resolution may be such that they are not mappable, or not identifiable in seismic. Subsurface coal mine abandonment plans may be of high enough resolution to identify these smaller offset faults.

Faults mapped by the BGS have only been occasionally directly observed in the field (i.e. along coastlines, quarries and opencast sites). They are often interpretations based on landscape features (e.g. zones of weakness utilised by drainage) or are used to solve geological problems where there is a lack of continuity across geological strata. The faults on the BGS maps are interpreted from field mapping, borehole information, mine abandonment plan data and seismic data and as such may not capture the full structural complexity of an area. The seismic data is of variable quality in the Midland Valley of Scotland, with the result that in some areas of poor data quality it is difficult to tie subsurface seismically interpreted structure to surface geology.

2.4.5 Regional Fault Trends

There are three dominant trends of major faults within the Midland Valley interpreted on BGS maps: E-W, ENE – WSW, and NW-SE. These structures are interpreted as having been active at times during the Devonian-Carboniferous to Permian periods (419 to 299 million years ago). The majority of the structures trend E-W and ENE-WSW, with a lesser population to the NW-SE. In general the Ayrshire coal fields are dominated by ENE-WSW faults, the Central Coalfield by E-W faults and Fife by NW-SE and ENE-WSW faults. BGS maps at 1:625,000 and 1:50,000 scale show the positions of major faults mapped at surface (Figure 2.9, Figure 2.10). However, numerous smaller faults have been identified in mine plans and by field mapping. In this section the three dominant trends of major faults in the Midland Valley at the 1:625 000 and 1:250 000 scale geology maps are described, before briefly considering the distribution of faults at the 1:50 000 scale. Note, description of the main faults within each 1:50 000 geological sheet are provided within the relevant geological memoir of the area (e.g. for Glasgow: Hall et al., 1998; for Falkirk: Cameron et al., 1998; for Edinburgh: Browne et al., in press).

**ENE - WSW trending faults**

This fault trend predominates in the western side of the Midland Valley of Scotland. Major faults which trend more or less parallel to the Midland Valley terrane bounding faults include the Dusk Water Fault, Paisley Ruck, Kerse Loch Fault, Pentland Fault, Ardross and Dura Den faults. These faults are interpreted as related to inherited crustal weakness from the Lower Palaeozoic tectonic events, as are the major Highland Boundary and Southern Upland bounding faults (Figure 2.2). The Paisley Ruck has a wide fault zone of up to 180 m, and has been described as a positive flower structure (Gibbs, 1984). Near Linwood, the fault downthrows strata to the north and has a displacement of up to 550 m, though usually less (Hinxman et al. 1920). The Dusk Water Fault dips at 85 degrees toward the south-east (Monaghan 2013).

**E – W trending faults**

There are few E-W trending mapped faults in the Ayrshire Coalfield at the larger scale e.g. between Stewarton and Kilmarnock three E-W unnamed trending faults are marked. In the Clackmannan and North East Stirlingshire Coalfields, the general trend of faulting is east-west and is considered neither severe nor closely-spaced (Jones, 2004). The major faults include the
Figure 2.9: Major onshore faults mapped at 1:625 000 scale BGS©NERC DigMap within the Midland Valley of Scotland. Faults are colour coded by orientation.
Figure 2.10: Major onshore faults mapped at 1:250,000 scale BGS©NERC DigMap within the Midland Valley of Scotland. This includes the major faults from the 1:625,000 scale. Note additional complexity and density of faults which is not captured at the 1:625,000 scale.
Abbey Craig, Alloa, Clackmannan and Kincardine Ferry faults, which all throw down to the south with maximum values in the range of 120 – 240 m (Jones, 2004). The East Ochil Fault (Rippon et al., 1996) forms the northern margin of the coalfield and has a vertical throw of at the most 1300 m (Browne and Woodhall, 1999). The East Ochil Fault was exposed during excavations in the Westfield Surface Coal Mine: the fault zone is steeply dipping at 65 degrees and of normal throw with a shatter zone up to 15 m wide (Browne and Woodhall, 1999; Rippon et al., 1996; Underhill et al., 2008). Other E-W faults in the coalfield south of the East Ochil Fault have moderate fault plane dips of around 45° to the south (Rippon et al., 1996).

Faults of this trend are a marked feature of the Fife coalfield region, including the Durie Fault, and the Balcormo Fault (Forsyth and Chisholm, 1977). The Campsie Fault, which bounds the north of the Central Coalfield, has a maximum throw of 1600 m but decreases markedly towards the east. The fault splits into northern and southern branches that extend for over 3 km and are up to 600 m apart (Forsyth et al., 1996).

**NW-SE trending faults**

The Sanquhar Basin lies in a half-graben bounded to the north-west by a splay of the Southern Upland Fault zone, and to the north-east by the Sanquhar Fault, a normal fault with overall downthrow of 580 m (Smith, 1999). The Sheardale and Arndean faults in the Clackmannan and North East Stirlingshire Coalfields have large downthrows to the south-west: the Sheardale Fault has a maximum downthrow of 200 m, and the Arndean over 1000 m (Francis et al., 1970). The Dechmont Fault is the largest NW trending feature in the Midland Valley of Scotland, with a downthrow of 650 m to the north-west (Hall et al., 1998).

### 2.4.6 Palaeozoic Fault Timing

There is evidence that the Midland Valley of Scotland underwent active tectonism including periods of faulting from the late Devonian through to the Late Carboniferous-early Permian (Table 2.2; Cameron and Stephenson, 1985; Read et al., 2002; Rippon et al., 1996; Underhill et al., 2008).

The ENE-WSW faults are interpreted as reactivated pre-existing structures formed during the Caledonian Orogeny. Many of the faults of east-west and NW-SE trend cut across the youngest Carboniferous rocks in the area and therefore date from latest Carboniferous or early Permian times (Paterson et al., 1998). By virtue of their association with latest Carboniferous-early Permian dykes, faults and extensional fractures, E-W striking faults and associated intra-basinal structures are dated at Latest Carboniferous (Browne & Woodhall, 1999; Rippon et al., 1996; Stephenson et al., 2003; Monaghan & Parrish 2006).

### 2.4.7 Faulting – a closer view

The BGS 1:625 000 and 1:250 000 geology maps give a regional overview of the major faults within the Midland Valley of Scotland. However, they cannot provide an accurate representation of the complexity of structures within the subsurface, such as providing intensity, density, spacing and extent, due to their large scales. The 1:50 000 geology map provides a more representative indication of this complexity (Figure 2.11), however it still does not capture the detail for small displacement (e.g. less than 10 m offset) faults that may be present in the subsurface but not extend to surface. This is in part due to scale, and also due to lack of natural exposures within the Midland Valley of Scotland. As such, small displacement faults have mostly been recorded in surface coal mines, or underground coal workings. In some circumstances, mining information can therefore provide a greater level of understanding of faulting in a particular coal seam for example. An examination of mine plans following coal extraction by Jones (2004; pages 112, 115, 117, 118, 119) provides an indication of the fault intensity in the subsurface of some of the coalfields:

- Ayrshire Coalfield: Intensively faulted
- Douglas Coalfield: Faulting is significant and may be closely spaced.
- Clackmannan and North East Stirlingshire coalfields: Faulting is neither severe nor closely-spaced
- Fife Coalfield: Faulting is neither severe nor closely-spaced
- Lothian Coalfield: Faulting is not severe but may be closely-spaced

<table>
<thead>
<tr>
<th>Time scale</th>
<th>Lithostratigraphy (after Browne et al. 1999)</th>
<th>Tectonic events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permian</td>
<td>Scottish Upper Coal Measures Formation</td>
<td>NW-SE trending faulting</td>
</tr>
<tr>
<td></td>
<td>Scottish Middle Coal Measures Formation</td>
<td>E-W trending faulting</td>
</tr>
<tr>
<td></td>
<td>Scottish Lower Coal Measures Formation</td>
<td></td>
</tr>
<tr>
<td>Carboniferous</td>
<td>Coal Measures Group</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Passage Formation</td>
<td>Dextral oblique-slip on reactivated Caledonide bounding structures. growth over E to ESE trending faults. NE-faults active in west.</td>
</tr>
<tr>
<td></td>
<td>Upper Limestone Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limestone Coal Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower Limestone Formation</td>
<td></td>
</tr>
<tr>
<td>Carboniferous</td>
<td>Clackmannan Group</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lawmuir Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kirkwood Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clyde Plateau Volcanic Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gullane Formation</td>
<td></td>
</tr>
<tr>
<td>Strathclyde Group</td>
<td>Clyde Sandstone Formation</td>
<td>Possible extensional rifting, NE-SW trends</td>
</tr>
<tr>
<td></td>
<td>Ballagan Formation</td>
<td>Possible sinistral oblique reactivation</td>
</tr>
<tr>
<td></td>
<td>Kinnesswood Formation</td>
<td>Acadian deformation, uplift and erosion</td>
</tr>
<tr>
<td>Inverclyde Group</td>
<td>Stratheden Group</td>
<td>Sinistral oblique reactivation of Caledonide faults generates Devonian-Carboniferous basins</td>
</tr>
<tr>
<td>Devonian</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2. Summary chart of Midland Valley of Scotland Carboniferous tectonic history (modified from Monaghan, 2014).

Field studies of the formations of interest provide a better understanding of fault scaling relationships within the rocks. An example is given from the Spireslack surface coal mine where an exposed Lower Limestone Formation limestone pavement which sits stratigraphically above a shale layer is faulted across the length of its exposure (Figure 2.12). Upon that fault plane, cross-cutting fault displacements range from 10 m to cm-scale. The detail of local scales of faulting cannot be captured on the regional maps presented here. The evidence from opencast coal sites visited by BGS geologists over many years and mine plans suggests great local variability in faulting density and style; some opencast sites examined have been largely free of natural faults, others have been complexly dissected by faulting at a variety to centimetre to kilometre scale.
Figure 2.11: 1:50 000 scale faulting BGS©NERC DigMap. The three dominant trends are still prominent, but the reality of fault spacing and density is better visualised at this scale. Some gaps in the fault dataset reflect the vintage of BGS mapping of the area.
Figure 2.12: Faulted limestone pavement, East Ayrshire. In addition to the faults which displace the limestone, there is a set of orthogonal fractures (with no offset) across the limestone. © BGS, NERC.

2.4.8 Cenozoic faulting

The Cenozoic Era encompasses the Palaeogene, Neogene and Quaternary periods and includes the present day. During the Palaeogene, a major phase of rifting occurred to the west of Scotland related to opening of the Atlantic Ocean. It is possible that some of the minor NW-SE structures and tensional fractures may be related to the intrusion of NW-SE orientated Palaeogene dyke swarms, formed due to sea-floor spreading in the north-east Atlantic (Cameron and Stephenson, 1985). Dykes of this age commonly occupy pre-existing Palaeozoic structures.

However, there is little direct evidence for Cenozoic faulting within the Midland Valley. Several master-joints in a NW to northerly trend in the Ochil Hills have been found to display recent movement, along lineaments less than 1km (Davenport et al., 1989). The Southern Uplands Fault has also been found to display evidence for movement during the late Palaeogene to Quaternary, with a suggestion of recent movement during post glacial times where the River Nith crosses the fault (Sissons, 1976; Davenport et al., 1989). Davenport et al., (1989) note that continuing minor activity at sites of post-glacial faulting is evident within the Midland Valley. These major structures along which recent faulting is observed are of an ENE-SWS to E-W trend (Davenport et al., 1989).
2.5 SPATIAL AND TEMPORAL CHARACTERISTICS OF EARTHQUAKE ACTIVITY

2.5.1 Earthquake Data

Earthquake information can be derived from two sources: historical archives containing references to felt earthquakes; and, earthquake source parameters derived from instrumental recordings of ground motions from earthquakes. The primary source of data for historical earthquakes in the British Isles from 1382 to present is the catalogue of Musson (1994), along with subsequent updates. This contains locations and magnitudes determined from the spatial variation of intensity, a qualitative measure of the strength of shaking of an earthquake determined from the observed effects on people, objects and buildings (e.g. Musson, 1996b).

The primary sources of data from 1970 to present are the annual bulletins of earthquake activity published by BGS each year (e.g. Galloway et al., 2013). These contain locations and magnitudes determined from recordings of ground motion on a network of sensors around the UK (e.g. Baptie, 2012). The bulletins also contain error estimates. Bulletin data are updated with revised parameter data published in BGS reports or peer-reviewed journal publications on specific earthquakes (e.g. Ottemoller et al., 2009).

Estimates of earthquake source parameters determined from historical data are generally subject to larger uncertainties than those determined from instrumental data. In addition, the completeness of these catalogues varies strongly with time. For example, Musson (1996a) states that prior to 1700 only the largest earthquakes are known about, whereas, from the 19th century on many smaller earthquakes are known about. The completeness of instrumental catalogues may also vary as a function of time as a result of changes to the monitoring network, e.g. an increase in the number of sensors in a given area.

Source parameters for both historical and instrumentally recorded earthquakes are combined in the BGS earthquake catalogue for the UK and immediate offshore area. Figure 2.13 (a) shows historical (yellow circles) and instrumentally recorded (red circles) earthquakes from this catalogue in Scotland. It is clear that there is significant spatial variation, with most earthquakes lying north of the Highland Boundary Fault and on west side of mainland Scotland. Northern and eastern Scotland shows relatively little earthquake activity. Earthquake activity is also lower in the Midland Valley, particularly in the instrumental period, though there is some evidence for historical earthquake activity.

The magnitude 5.2 ML Argyll earthquake in 1880 is the largest known Scottish earthquake and was felt along the west coast of Scotland, east as far as Perthshire and throughout the Hebrides. Earthquakes with magnitudes of 5.1 and 5.0 ML occurred in Inverness in 1816 and 1901. The 1901 earthquake was felt over much of Scotland and caused substantial amounts of minor damage in Inverness, including falling chimneys and masonry. The earthquake was followed by an aftershock sequence that lasted some months.

Comrie, on the Highland Boundary Fault experienced earthquake swarms (sequences of earthquakes clustered in time and space without a clear distinction of main shock and aftershocks) between 1788 and 1801, and again between 1839 and 1846. The largest event in this sequence was a magnitude 4.8 ML event in 1839. The magnitude 4.4 ML Kintail earthquake in 1974 is the largest instrumentally recorded earthquake in the catalogue. This was the largest in a swarm of over 20 events that occurred over several months.

Our initial analysis is based on the instrumental catalogue (1970-present). This contains 4526 earthquakes, 329 of which have magnitudes of 2.0 ML or greater. The minimum and maximum recorded magnitudes are -0.7 ML and 4.4 ML, respectively. There are five earthquakes with a magnitude of 4.0 ML or greater including the magnitude 4.4 Kintail earthquake, as well as two other earthquakes in the Kintail sequence. The other two are the magnitude 4.1 ML Oban earthquake in 1986 and the magnitude 4.0 ML Arran earthquake in 1999.
Earthquake magnitude is a measure of the amount of energy released during an earthquake and is determined from the amplitude of the ground motions caused by the earthquake. We also need to know how far away the earthquake was because the amplitude of the seismic waves decreases with distance, so we must correct for this. The first magnitude scale was developed by Charles Richter in 1935, based on observations of earthquake ground motions in California. Although this magnitude scale is only strictly applicable in California, it has been used all around the world and is commonly referred to as Local Magnitude, ML.

Magnitude scales are logarithmic so that each whole number increase in magnitude represents a tenfold increase in measured amplitude and about 32 times the energy released. Seismic moment is usually estimated directly from recordings of earthquake ground motions.

How the Richter’s magnitude Scale works. The amplitude is measured from the recording of ground motions at a specific site, as is the distance from the earthquake. A line connecting the two values on the graph gives the magnitude of the earthquakes.

A number of different magnitude scales have been developed; however, the most standard and reliable measure of earthquake size is moment magnitude, MW, which is based on seismic moment, which is related to both the area of the rupture and the displacement on the rupture.

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Earthquake Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 or less</td>
<td>Usually not felt, but can be recorded by seismograph.</td>
</tr>
<tr>
<td>2.5 to 5.4</td>
<td>Often felt, but only causes minor damage.</td>
</tr>
<tr>
<td>5.5 to 6.0</td>
<td>Slight damage to buildings and other structures.</td>
</tr>
<tr>
<td>6.1 to 6.9</td>
<td>May cause a lot of damage in very populated areas.</td>
</tr>
<tr>
<td>7.0 to 7.9</td>
<td>Major earthquake. Serious damage.</td>
</tr>
<tr>
<td>8.0 or greater</td>
<td>Great earthquake. Can totally destroy communities near the epicenter.</td>
</tr>
</tbody>
</table>

The table shows the expected effects for different earthquake magnitude ranges.
Figure 2.13. (a) Historical (yellow circles) and instrumentally recorded (red circles) earthquakes from the BGS catalogue for Scotland. Circles are scaled by magnitude. (b) Seismograph stations operated by BGS between 1970 to present. Note that not all station were operational at the same time. (c) Cumulative number of earthquakes as a function of time from 1970 to present. Blue line shows all recorded earthquakes. The red line shows earthquakes with magnitudes of 2.0 ML and above. (d) Annual number of earthquakes from 1970 to present. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016.

Figure 2.13 (b) shows seismograph stations operated by BGS between 1970 and present. Note that not all stations were operational at the same time. Figure 2.13 (c) shows the cumulative number of events from 1970 to 2015. The blue line shows all recorded earthquakes, while the red line shows earthquakes with magnitudes of 2.0 ML and above. Since the natural earthquake activity rate is expected to remain constant over long periods of time, the cumulative number of events should show a linear gradient. This is approximately the case for earthquakes of magnitude of 2.0 and above, so the observed changes in gradient may be related to changes in
the detection capability of the network or the inclusion of dependent events such as aftershocks in the catalogue. For example, there are jumps of seismicity rare following the occurrence times of the Kintail and Oban earthquakes, which may be related to aftershocks. Figure 2.13 (d) shows the annual number of events from 1970 to present.

2.5.2 Mining Induced Seismicity

The coalfields of Britain have frequently been the source areas of small to moderate earthquakes and tremors in these areas have been reported for at least the last hundred years, for example the Stafford earthquake of 1916 (Davison, 1919). With the growth of instrumental seismic monitoring in the UK in the 1970’s, many more tremors were recorded in mining areas across the UK (Redmayne et al., 1988) and a number of temporary networks of sensors were deployed to study these events in more detail. This led to the conclusion that these events were related to ongoing mining activity and that these were quite distinct from the natural background seismic activity of the UK. Tremors around Stoke-on-Trent, Staffordshire in the period 1975-1977 were shown to originate from a region above active mine-workings (Westbrook et al., 1980). A network deployed around Rosslyn Chapel in the Midlothian coalfield recorded over 250 earthquakes between 1987-1990 that were shown to have a close spatial and temporal association with mining activity (Redmayne et al., 1998). Between July 1989 and August 1990 over 130 tremors were felt and reported by people in the Edinstowe district of Nottinghamshire. A temporary network of sensors detected a further 785 microseismic events in the following 11 months helping to establish a causal relationship between the local microseismicity and coal production (Bishop et al., 1994).

In the 1980’s and 1990’s mining events accounted for approximately 25% of all the earthquakes recorded in the UK (Browitt et al., 1985). Since the rapid decline of mining activity in the UK there has been a general decrease in the number of these events. The identified area of potential UOG development coincides with areas of high-density coal-mining in the Midland Valley, and since these mining induced events represent a temporary perturbation they need to be removed from the earthquake catalogue so that an accurate measure of natural earthquake activity rates can be established. We do this by defining a simple spatial filter based on the Mining Reporting Areas, as issued by the Coal Mining Authority. All events from within these areas are removed from the catalogue.

Figure 2.14(a) shows the spatial distribution of both natural and mining induced seismicity (red circles) in the Midland Valley region overlaid on the Mining Reporting Areas (grey shaded areas). Also shown are events that were identified as mining-induced during analysis (black circles). There are a large number of earthquakes within the Mining Reporting Areas, particularly in the Midlothian and Clackmannanshire coalfields. It is also clear that there are many events in these areas that have not been classified as suspected mining induced events but are likely to be so, given the strong spatial and temporal correlation with other mining induced earthquakes.

Figure 2.14(b) shows the cumulative number of both natural (green line) and coal-mining (red line) events as a function of time. The rate of both natural and mining induced events is approximately constant through the 1970’s, 1980’s and 1990’s, with the majority of the events being of suspected coal-mining origin. By the late 1990’s the number of mining events begins to fall resulting in little subsequent increase in cumulative number of events, whereas the cumulative number of natural events continues to increase at approximately the same rate as previous. With this in mind, we consider that any events in the Mining Reporting Areas post-2000 are natural events rather than mining-induced, although stoop and room collapses may occur after mining has stopped.
In theory, earthquake focal depth could also be used to discriminate between natural and mining-induced earthquakes since we expect mining-induced earthquakes to occur at shallower depths (0-2 km), whereas natural earthquakes are generally deeper. However, examination of the focal depth distribution of earthquakes in the Mining Reporting Areas (Figure 2.15(a)) shows that depths for earthquakes prior to 1982 are primarily fixed depth hypocentral solutions rather than seismicity concentrated in the first 2 km. The subsequent improvement of the network resulted in independent hypocentral determination of seismic events with focal depths spanning the active shallow crust (0-12 km). The majority of events (>80%) are shallower than 5 km depth indicating many fewer earthquakes at larger depths over this time period. However, the large uncertainties mean that the use of depth as a discriminant becomes unreliable.

Figure 2.15 (b) shows the magnitude distribution over time of earthquakes in the Mining Reporting Areas. The maximum observed magnitude is 2.6 ML, with an average reported magnitude approximately ~ML=1.0. Furthermore, we observe a lower activity rate post-2000, suggesting that activity is returning to the background activity rate for natural earthquakes.

The maximum observed magnitudes from coal mining induced seismicity in the UK (Bishop et al., 1994 and Redmayne et al., 1998) is around 3 ML. The three largest events had magnitudes of 3.1 ML and occurred in Mansfield and Stoke. These were felt with an intensity of 4 EMS. However, other mining induced earthquakes with smaller magnitudes have been felt with higher intensities, for example, a magnitude 2.3 ML event at Rosewell in Midlothian was felt with an intensity of 5 EMS.
Figure 2.15 (a) Focal depths as a function of time for earthquakes in the Mining Reporting Areas. (b) Magnitudes of mining induced earthquakes as a function of time. The deeper earthquakes may be natural seismicity. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016.

2.5.3 Earthquake Activity Rates

After removing the mining-induced seismicity, we use the revised catalogue from 1970 to 2015 to determine activity rates for background natural earthquake activity both for all of Scotland and for the Midland Valley study area. To ensure that the results are credible, we compare them with activity rates determined for historical earthquakes over the last few hundred years. These estimates of past activity rates can be used to make forecasts of future earthquake activity.

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

\[ \log_{10} N = a - bM \]

where \( N \) is the number of earthquakes above a given magnitude \( M \). The constant \( a \), is a function of the total number of earthquakes in the sample and is known as the earthquake rate. This is commonly normalised over period of time, such as a year. The constant \( b \) gives the proportion of large events to small ones, and is commonly referred to as the \( b \)-value. In general, \( b \)-values are...
close to unity. This means that for each unit increase in magnitude, the number of earthquakes reduces tenfold. Plotting earthquake magnitudes against the logarithm of frequency (Figure 2.16) gives a straight line, where the slope of the line is the $b$-value and the rate, $a$, is the value where the line intersects with a given reference magnitude (often zero). An observed roll-off in the number of earthquakes at low magnitudes shown by the blue crosses in Figure 2.16 is typically seen due to inability of regional seismic networks to detect small earthquakes.

This roll-off in the magnitude-frequency relationship at low magnitudes leads to the concept of a completeness magnitude, $M_c$, which can be defined as the lowest magnitude at which 100% of the earthquakes in a space-time volume are detected (Rydelek and Sacks, 1989). The use of too low a value of $M_c$ will generally result in underestimates of both $a$ and $b$ values. With this in mind it is important to select appropriate values of $M_c$ when calculating these parameters.

![Figure 2.16](image)

**Figure 2.16.** Schematic showing the number of earthquakes above a given magnitude plotted against magnitude. This shows an exponential distribution leading to the Gutenberg-Richter law. The slope of the lines is the $b$-value and determines the relative number of earthquakes of different magnitudes. An observed roll-off in the number of earthquakes at low magnitudes shown by the blue crosses is typically seen due to inability of regional seismic networks to detect small earthquakes. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016.

Firstly, we use only the instrumentally recorded earthquakes in the Scottish catalogue from 1970 to 2015, with the mining earthquakes removed, to estimate earthquake activity rate by applying a penalised maximum likelihood procedure (e.g. Johnston et al., 1994). We assume that the catalogue is complete for magnitudes of 2.0 and above. The results are shown in Figure 2.17 (a), and give an activity rate of 2.79 and a $b$-value of 0.95. This is equivalent to eight earthquakes with a magnitude of 2.0 or above occurring somewhere in Scotland every year.

Similarly, analysing seismicity in the Midland Valley, we find 6 events with $M \geq 2.0$ for the time period 2000-2015, corresponding to an activity rate 0.3750 events/year. Figure 2.17(b) shows the frequency magnitude distribution in Midland Valley for the time period of 1970-2015. This gives an activity rate of 2.75 and a $b$-value of 1.33, equivalent to 1.2 events with a magnitude of 2 or above somewhere in the Midland Valley every year. The large number of low-magnitude mining earthquakes in the Midland Valley results in the much higher $b$-value.

Next we determine an activity rate using only historical earthquakes in the Scottish catalogue from 1597 to 1969 using the same method, specifying different magnitude of completeness
thresholds for different time intervals of the catalogue (Table 2.3) following Musson and Sargeant (2007). In this case, we consider a minimum magnitude of 3.0. The results are shown in Figure 2.17 (b), giving an activity rate, of 2.987 and a recurrence parameter, b, of 1.015. These values are broadly consistent with the results for the instrumental catalogue only, and are equivalent to nine earthquakes with a magnitude of 2.0 or above occurring somewhere in Scotland every year.

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Date</th>
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<tbody>
<tr>
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<td>1970</td>
</tr>
<tr>
<td>3.5</td>
<td>1850</td>
</tr>
<tr>
<td>4.0</td>
<td>1750</td>
</tr>
<tr>
<td>4.5</td>
<td>1700</td>
</tr>
<tr>
<td>5.0</td>
<td>1650</td>
</tr>
<tr>
<td>6.5</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 2.3. Magnitude of completeness for different periods of time used for Britain by Musson and Sargeant (2008).

![Figure 2.17](image-url) Magnitude-Frequency distributions for: (a) instrumentally recorded seismicity in Scotland from 1970-2015; (b) instrumentally recorded seismicity in the Midland Valley from 1970 to 2015; (c) historical seismicity in Scotland from 1597 to 1969; and (d) historical and instrumentally recorded seismicity in the British Isles. The blue squares show the observed data. The blue straight lines show the best-fit to the data for a Gutenberg-Richter distribution. The $a$ and $b$ values are given in the top right of each plot. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016.

Finally we calculate an activity rate using the historical and instrumental earthquake catalogue for all of the British Isles using magnitude of completeness thresholds for different time intervals.
in Table 2.3. Again, we consider a minimum magnitude of 3.0. The results are shown in Figure 2.17 (d), giving an activity rate, of 3.67 and a recurrence parameter, b, of 1.0. Both values are in keeping with the results obtained by Musson and Sargeant (2007) using only instrumental data.

2.6 THE REGIONAL STRESS FIELD AND FAULT REACTIVATION POTENTIAL

The pre-existing state of stress on a fault partly determines how close it is to failure. Although the magnitude of the ambient stress field in the Earth cannot be directly measured, borehole experiments from stable continental regions suggest that a critical state of stress is expected at any depth throughout the Earth’s Crust (Townend and Zoback, 2000). This suggests that even small stress perturbations may cause an active fault to fail.

Earthquake focal mechanisms provide both fault geometries and principal stress directions that can be used to constrain our understanding of the driving forces of current deformation. In areas of low seismicity and sparse station distribution, determining reliable focal mechanisms can be problematic. This means that available mechanisms for earthquakes in Scotland are limited to larger events of ML≥3.5/4.0, as it is generally not possible to calculate mechanisms for smaller events. Figure 2.18 (a) shows focal mechanisms available for earthquakes in Scotland (Baptie, 2010), along with the mechanism for the 1979 Carlisle earthquake. The blue shaded areas show directions where the initial motion of the seismic waves is up (compressional), while the white areas show directions where the initial motion of the seismic waves is down (dilatational). The directions of the maximum and minimum compressive stresses are shown by the blue and white squares, respectively.

The resulting focal mechanisms are mainly strike-slip with N-S compression and E-W tension. This results in either left-lateral strike-slip faulting along near vertical NE-SW fault planes, or right-lateral strike-slip faulting along near vertical NW-SE fault planes. Some of the events also have an oblique component to the slip (e.g. Dunoon, 1985; Aberfoyle, 2002).

The World Stress Map (Heidbach et al., 2010) contains \( s_H \) (maximum horizontal compressive stress) orientations for the British Isles determined from a variety of stress indicators including borehole breakouts (e.g. Williams et al., 2015), drilling induced fracturing and hydro-fracturing as well as previously published focal mechanisms (Baptie, 2010). Borehole breakouts are enlargements or elongations in the cross-section of a wellbore in a direction parallel to the minimum (least) horizontal stress. Figure 2.18 (b) shows smoothed stress orientations on a 0.5° grid from the World Stress Map. The orientation of \( s_H \) is roughly N-S in the north of Scotland, rotating to a more NW-SE direction in the north of England. This agrees reasonably with the focal mechanisms in the north of Scotland, however, the smoothed \( s_H \) values are based on sparse data, most borehole breakout data are from offshore areas (e.g. Williams et al., 2015), and there are no good stress data for the Midland Valley of Scotland.

Horizontal maximum and minimum compressive stress directions will result in strike-slip faulting on near vertical fault planes, as is widely observed in the British Isles (Baptie, 2010). If the maximum compressive stress direction is N-S then faults that strike NE-SW will be optimally oriented for left-lateral strike-slip motion, while faults that strike NW-SE will be optimally oriented for right-lateral strike-slip motion. This means that faults such as the Highland Boundary Fault, or the Great Glen fault, which strike NE-SW are most likely to show left-lateral strike-slip.

Given the observed N-S compression and E-W tension, the reactivation potential for near-vertical E-W or ENE-WSW striking faults in the Midland Valley region will be low. However, if the maximum horizontal compressive stress direction does rotate to a more NW-SE direction then the reactivation potential for these fault populations will increase.
Figure 2.18. (a) Focal mechanisms available for earthquakes in Scotland (Baptie, 2010). The blue and white areas show the compressional and dilatational quadrants and the lines between the quadrants show the strike and dip of the two possible fault planes. The axes of maximum and minimum compression are indicated by the blue and white squares respectively. The blue squares on the map show the location of the earthquakes. (b) a comparison of the stress field with mapped fault orientations. The black lines show the orientation of the maximum horizontal compressive stress, $s_H$, taken from smoothed stress orientations published in the World Stress Map (Heidbach et al., 2010). Green lines show mapped faults. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016.

FOCAL MECHANISMS

Seismologists refer to the direction of slip in an earthquake and the orientation of the fault on which it occurs as the focal mechanism. This can be determined from recordings of seismic waves and is typically displayed as a "beach ball" symbol. The dividing lines between the quadrants on the beach-ball define the orientation of the fault planes and the directions of slip.

The schematic shows examples of focal mechanisms for four different types of faulting. If the rocks on either side of the fault slide horizontally past each other this is strike-slip faulting (a). This can be either left or right-lateral depending on which direction the rocks on the far side of the fault move. In this case the focal mechanism projection divides into four quadrants. Vertical dip-slip faulting (b) occurs when the fault plane is vertical and the fault motion is in a vertical direction. In this case the focal mechanism projection divides in two. Normal faulting (c) occurs when the upper fault block slides down relative to the lower block. Reverse faulting (d) occurs when the lower fault block slides down relative to the upper block.

Commonly, shaded or coloured areas show directions where the initial motion of the seismic waves is up (compressional), while the white areas show directions where the initial motion of the seismic waves is down (dilatational).
2.7 DISCUSSION

The earthquake catalogue for the study area and for Scotland consists of earthquake information determined from both historical records and instrumental recordings of ground motions. The completeness of this catalogue varies in both time and space. The earliest historical record of an earthquake dates from 1597 and there are regular reports of earthquakes throughout the 17th and 18th centuries. The magnitude 5.2 ML Argyll earthquake in 1880 is the largest known Scottish earthquake, while the magnitude 5.1 ML Inverness earthquake in 1901 is the most damaging. The catalogue is assumed to be complete for earthquakes with magnitudes of 4.0 and above from 1750 to present.

The installation of sensors to measure ground motions from earthquakes from 1970 on resulted in a dramatic increase in the number of earthquakes recorded. Over 4000 earthquakes were recorded in Scotland between 1970 and the end of 2015. Although the completeness of the catalogue also varies in space and time, we estimate that it is reasonably complete for magnitudes of 2.0 and above. There are 363 earthquakes in the catalogue above this magnitude from 1970 to the end of 2015.

The identified area of potential UOG development coincides with areas of high-density coal-mining in the Midland Valley and there are a large number of instrumentally recorded earthquakes within the Mining Reporting Areas, as issued by the Coal Mining Authority. The dramatic decline in the number of mining induced earthquakes in the last two decades shows that the mining induced earthquakes have been a temporary perturbation, which needs to be removed from the earthquake catalogue so that an accurate measure of natural earthquake activity rates can be established. We attempted to remove these by defining a simple spatial filter based on the Mining Reporting Areas. Over 2000 mining-induced earthquakes were removed from the catalogue this way.

The low number of earthquakes observed in the Midland Valley from 2000 to present suggests that activity is returning to the background rate for natural earthquakes. While the number and frequency of mining induced earthquakes is expected to further decline in future, such earthquakes may still occur. As a result, it may be difficult to discriminate such events with events induced by other future industrial activities such as hydraulic fracturing using seismic data alone.
Earthquake activity rates for Scotland determined from the instrumental catalogue only suggest that, on average, there are eight earthquakes with a magnitude of 2.0 or above somewhere in Scotland every year. This is reasonably good agreement with activity rates determined using historical data. Activity rates in the Midland Valley area are less that the average for Scotland, although the small number of earthquakes in catalogue for this area means the values are poorly constrained. However, it is clear that there is less than one earthquake with a magnitude of 2 or above in this region annually. Activity rates in Scotland are lower than the average for the British Isles.

It is difficult to associate earthquakes with specific faults because of: (a) uncertainties in the earthquake location, especially depth, which are typically several kilometres; (b) uncertainties in fault distributions and orientation at depth; and, (c) the limited size of the earthquakes means the rupture dimensions are small. A few of studies (e.g. Ottemöller and Thomas, 2007) have used the alignment of earthquakes from a specific sequence, along with earthquake focal mechanisms, to identify causative faults. However, most of the earthquakes in the catalogue cannot be associated with a specific fault.

The limited number of focal mechanisms for earthquakes in Scotland, along with other reliable stress indicators such as borehole breakouts means that there is a lack of detailed information on the spatial variation of stress directions across Scotland. The observed orientation of the maximum and minimum compressive stresses means that the reactivation potential of faults that strike either NE-SW or NW-SE are interpreted, based on existing data, to be highest, with the former optimally oriented for left-lateral strike-slip motion. This means that fault systems that follow the widely observed Caledonian trend may have a higher reactivation potential than other orientations. However, the reactivation potential for near-vertical E-W or ENE-WSW striking faults in the Midland Valley region is interpreted to be low based on current data. This seems in keeping with the low levels of observed seismicity in this part of Scotland. However, if the maximum horizontal compressive stress direction does rotate to a more NW-SE direction as suggested by smoothed values of $S_H$ from the World Stress Map over the Midland Valley of Scotland, then the reactivation potential for these fault populations is higher. Given the limitations of the existing data (focal mechanisms as well as other stress indicators) it is not possible to identify any particular parts of the study area where the fault reactivation potential is higher or that may present an elevated seismic hazard for any UOG operations.
3 International and UK experience of induced seismic activity arising from hydraulic fracturing

3.1 OVERVIEW

A review of induced seismicity in UOG operations confirms that the probability of felt earthquakes caused by hydraulic fracturing for recovery of hydrocarbons is very small. In the US over 1.8 million hydraulic fracturing operations for shale gas recovery have been carried out and there are only three documented cases of induced earthquakes. The largest of these earthquakes had a magnitude of 3.0. In western Canada, there is evidence of increases in the annual numbers of earthquakes and a number of documented examples of earthquakes with magnitudes larger than 3 in Canada that have been linked to hydraulic fracturing for shale gas recovery. The largest of these was a magnitude of 4.4 earthquake.

Recent increases in earthquake rates and significant earthquakes in many areas of the Central and Eastern United States have been linked to wastewater injection in deep disposal wells rather than hydraulic fracturing, and provide a considerable body of evidence that this activity presents a non-negligible risk of damaging earthquakes. Seismic hazard forecasts for the Central and Eastern United States show increases in earthquake hazard by a factor of 3 or more in some areas of induced earthquake activity. However, although many wastewater injection wells can be associated with earthquakes, the majority are not. Additionally, the nature of the wastewater injected into deep wells varies and while some comes from hydraulic fracturing used in unconventional oil and gas production, much of this is produced water from conventional hydrocarbon production.

3.2 BACKGROUND

The process of hydraulic fracturing in order to increase the permeability of reservoir formations and stimulate the recovery of hydrocarbons is also generally accompanied by microseismicity, commonly defined as earthquakes with magnitudes of less than 2.0 that are too small to be felt. Mapping this microseismicity during hydraulic fracturing operations is widely acknowledged as the best means of characterising stimulated fracture networks in unconventional reservoirs (Maxwell, 2010). Induced seismicity during hydraulic fracture operations has been discussed by a number of authors in the last few years, including Shetema et al. (2012), Warpinski et al. (2012) and Ellsworth (2013).

A report by the National Research Council in the U.S. (NAS, 2012), which examined the scale, scope and consequences of seismicity induced during fluid injection and withdrawal related to energy technologies, concluded that the process of hydraulic fracturing a well, as presently implemented for shale gas recovery, does not pose a high risk for inducing felt seismic events. Similarly, a Royal Society and Royal Academy of Engineering report (2012) also examined the risks associated with hydraulic fracturing during shale gas exploration and production, concluding that the surface impacts of any seismicity induced by hydraulic fracturing would be negligible.

However, there have also been a number of documented examples of rather larger induced earthquakes during hydraulic fracturing operations in both the United States (Holland, 2013) and particularly Canada (BC Oil and Gas, 2012, 2014; Atkinson et al., 2015, 2016; Schultz et al., 2015). The largest of these events had a magnitude of 4.4 Mw, which is, to date, the largest known earthquake induced by hydraulic fracture operations in a hydrocarbon field anywhere in the world.

In this section, we present an extensive review of induced seismicity in UOG operations. Limited data is available globally, and we focus on three geographic areas: central and eastern United
States; the West Canada Sedimentary Basin; and Blackpool, UK. Given the limited data available, we also discuss examples of recent seismicity related to waste-water disposal in the eastern United States. We will examine available UOG data from recent examples, such as induced seismicity in Blackpool, UK, as well as data from other analogues to investigate the controlling factors on induced seismicity during fluid injection and examine the relationships between injection volume and pressure and induced seismicity.

### 3.3 EXPERIENCE IN THE UNITED STATES

In the US, where ~1.8 million hydraulic fracturing operations have been carried out in ~1 million wells (Gallegos and Varela, 2014), felt seismicity induced by hydraulic fracturing appears to be extremely rare and there are only a handful of documented cases of hydraulic fracture induced earthquakes (Holland, 2013; Friberg et al., 2014; Skoumal et al., 2015). The magnitudes of the induced earthquakes in reservoirs such as the Barnett Shale (Maxwell et al., 2006) and the Cotton Valley (Holland, 2011) are typically less than 1 Mw. However, it should be pointed out that most sites of UOG operations lack independent instrumentation for monitoring induced seismicity and that earthquakes with magnitudes of 2.5 or less will fall below the detection thresholds of regional seismic monitoring networks.

Figure 3.1 shows seismicity of Texas and South Oklahoma along with some of the main shale gas plays in the region. The US catalogue\(^2\) contains 7992 events in this region in the period 1850 to present. Fewer than 450 of these are in Texas, of which 149 have M ≥ 3.0.

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The Barnett Shale extends over a total area 72,000 km² and is present across the Fort Worth Basin in north-central Texas (Bruner and Smosna, 2011). The Fort Worth Basin is mapped at surface, though toward the east of the area it is overlain by rocks of Cretaceous age. The Barnett Shale is Mississippian in age (middle Carboniferous), and formed in a foreland basin, created along the margin of convergent tectonic plates (Bruner and Smosna, 2011; Montgomery et al., 2005). The basin is bordered by a NE-SW trending thrust belt (Ouachita Structural Front) and the Muenster Arch, a basement high (Bruner and Smosna, 2011). The shale members are composed of distinct shale units separated by limestone units locally (Montgomery et al., 2005). The unit varies in thickness from 15 to 305 m, but most production is from the northern part of the basin where it is relatively thick (Montgomery et al., 2005). The Barnett Shale is underlain by the Ellenburger Group which is karstified, resulting in high-angle normal faults, karst fault-chimneys and local subsidence features in the Barnett Shale (Bruner and Smosna, 2011). One set of natural fractures with a strike of 100-120 is recognised in the Barnett (Bruner and Smosna, 2011), formed by tectonic movements during the Ouachita Orogeny. A map of the Barnett Shale in Frohlich (2012) shows mapped faults with a dominant NE-SW trend in the south-eastern part of the Barnett Shale, and a lesser population of faults with a NW-SW trend in the north-western part of the Barnett Shale.

Figure 3.2 shows the cumulative number of earthquakes in Texas as a function of time between 1975 and 2015. It is clear that between 1975 and 2005, the number of earthquakes increases at a constant rate, whereas after 2005 it starts to increase. As in other parts of Central and Eastern North America this increase in seismicity rates has been attributed to the injection of brines from oil and gas production into wells that are drilled to dispose of large volumes of waste water over many years (Ellsworth, 2013), and Frohlich et al. (2011) attribute a sequence of earthquakes in the Dallas-Fort Worth region to the disposal of waste-water in deep injection wells.

![Figure 3.2](image_url)

**Figure 3.2.** Cumulative number of earthquakes in Texas as a function of time between 1975 and 2015. The red squares show all magnitudes, the blue crosses show events of magnitude 3.0 or above. Earthquake data from the U.S. Geological Survey (USGS) ComCat

In the time period from 1975 to 2005 there were 53 earthquakes with a magnitude of 3 or greater in Texas, and, assuming that the catalogue is complete for events of this magnitude and above in this time period, this corresponds to an annual rate of 1.767.

The annual rate for magnitude 3.0 events in Scotland is 0.871, based on the $a$ and $b$ values calculated from the instrumental catalogue of 2.79 and 0.95 respectively. Forty-nine earthquakes
with magnitudes of 3.0 or above have been observed in the time period from 1970 to 2014. Scaling the calculated rates by area gives rates of $2.54 \times 10^{-06} / \text{km}^2$ and $7.25 \times 10^{-06} / \text{km}^2$ for Texas and Scotland respectively.

### 3.4 EARTHQUAKES INDUCED BY HYDRAULIC FRACTURING OPERATIONS NEAR BLACKPOOL, UK

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, on 1 April 2011, had a magnitude of 2.3 and was felt locally. The hydraulic fracturing was carried out during exploration of a shale gas reservoir in the Bowland basin, Lancashire. A further magnitude 1.5 ML earthquake was felt on 27 May, 2011 and also linked to hydraulic fracturing, leading to the suspension of operations at Preese Hall.

The seismicity led to a number of detailed studies of the relationship between the earthquakes and hydraulic fracturing operations (for example, de Pater and Baisch 2011; Eisner et al., 2011). In total, 58 earthquakes were detected in the time period between 31 March and 30 August 2011, nearly all of these occurred either during or within a few hours of fracturing operations at Preese Hall. De Pater and Baisch (2011) concluded that the earthquake activity was caused by fluid injection directly into a nearby fault zone, which reduced the effective normal stress on the fault and caused it to fail repeatedly in a series of small earthquakes. A possible causative fault was later identified following a detailed 3-D seismic reflection study (Clarke et al., 2014).

![Figure 3.3](image.png)

Figure 3.3. Volume of injected fluid (blue line) and earthquakes (red circles, scaled by magnitude) during hydraulic fracturing operations at Preese Hall, Blackpool, between March and June 2011 (after de Pater and Baisch, 2011). There are five distinct hydraulic fracturing 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. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016. Injected fluid volumes provided by Cuadrilla Resources, 2011.

Figure 3.3 shows the injected volume of fluid as a function of time in each of the hydraulic fracture stages carried out at Preese Hall along with the recorded earthquake activity (from de Pater and Baisch, 2011). It is clear that the earthquakes correlate strongly with stages 2, 4 and 5, in which the largest amount of fluid was injected. In two of the hydraulic fracturing stages, 2 and 4, the largest earthquakes occurred approximately ten hours after the start of injection, while the well was shut-in under high pressure. These events were preceded by smaller events, which started immediately after injection, the largest of which was a magnitude 1.4 ML event on 31 March.

No seismicity was observed during stages 1 and 3, and only very weak seismicity occurred during stage 5. The lack of seismicity in stage 3 can be attributed to the smaller pumped volume and the use of flowback. The pumped volume in stage 5 was similar to stages 2 and 4, but there
was also flowback, which could explain the lack of larger events. The results show that injected volume and flowback timing are important controlling factors in the level of seismicity, as evidenced from the lack of seismicity during and after stage 3, suggesting that seismicity can be mitigated by modifying job procedure.

Locations for the Blackpool earthquakes were determined by Eisner et al. (2011) and Clarke et al. (2014) among others. Similarity between the recorded events suggested that all the events were from the same location and had the same mechanism. The location is shown in Figure 3.4. It is clear that the location is less than 0.5 km from the well head. In addition, the depths of 3.6 km and 2.9 km, estimated by Eisner et al. (2011) and Clarke et al. (2014) are close to the point of injection (2.3 – 2.7 km) for all 6 stages.

Figure 3.4. Epicentre of Preese Hall earthquakes in April and May 2011 (yellow star), as determined by Eisner et al. (2011). The coloured triangles in (a) show permanent monitoring stations operated by the British Geological Survey at epicentral distances of 75 to 99 km (red), 100 to 149 km (orange) and greater than or equal to 150 km (yellow). The red triangles in (b) show temporary stations deployed after the initial earthquakes on 1 April 2011. The blue triangle shows the location of the Preese Hall well. Topography © Crown Copyright 2016 Ordnance Survey 10037272. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016.

The Bowland Basin is a thick accumulation of Carboniferous shales, bounded by two NE-SW trending faults (Andrews, 2013). The target for hydraulic fracturing was the Bowland-Hodder unit, a shale-dominated facies up to 1900 m thick, with limestones and turbidite deposits (Andrews, 2013). As in the Midland Valley of Scotland, the NE-SW structural trend is inherited from crustal weaknesses formed in the Lower Palaeozoic (during the Caledonian Orogeny). Fault systems are often normal, with a strong NE-SW influence and formed toward the end of the Carboniferous. There is no surface outcrop of the Carboniferous strata in this area (the strata are overlain at surface by rocks of Triassic and Permian age) and as a result little was known about the density or frequency of faults. The area is assumed to have had no substantial fault activity since the Permian Period (Clarke et al., 2014).

At a regional scale, the Carboniferous geology buried at depth beneath the Blackpool-Preese Hall area could be considered a continuation of the Ribblesdale Fold Belt. Within the Lancashire Coalfield some 30 km to the south-west of Preece Hall, where the Carboniferous rocks are exposed at surface, the density of faulting as mapped by BGS at 1:50,000 scale is similar to that in the Central Coalfield of the Midland Valley of Scotland.
3.5 EARTHQUAKES INDUCED BY HYDRAULIC FRACTURING IN THE HORN RIVER BASIN, BRITISH COLUMBIA

Over 200 earthquakes were induced during hydraulic fracturing operations in the Etsho and Tattoo fields in the Horn River Basin, British Columbia, during 2009-2011 (BC Oil and Gas Commission, 2012). The locations of these events are shown in Figure 3.5. The Horn River Basin lies in northeast British Columbia, between Fort Nelson and the Northwest Territories border, with a total area of 11,500 km$^2$, of which ~350 km$^2$ is used for oil and gas exploration and production. The Horn River Group shales occur throughout the basin and are a target for hydrocarbon extraction and exploitation. The shales and associated limestones are Devonian in age and lie at depths of over 2000 m (McPhail et al., 2008), with combined thicknesses of over 400 m in places. The shales are, for the most part, overlain by rocks of Mesozoic (Cretaceous) age.

The basin is bounded to the west by the Bovie Fault, a broadly NNE-SSW trending compressional-fault structure which extends over 200 km, from northeast British Columbia into southern Northwest Territories (Maclean and Morrow, 2004). The fault was established during the late-Carboniferous to early Permian, with motion renewed during the Cretaceous (Maclean and Morrow, 2004). The area is also intersected by the Trout Lake Fault Zone, a long, linear, NE-SW trending basement fault (Williams, 1977). Fault mapping by operators found abundant,

Figure 3.5. Location of the Etsho and Tattoo areas in the Horn River Basin (after BC Oil and Gas Commission, 2012). Red circles show the NRCan reported epicentres (scaled by magnitude). Small black dots show well positions. Black squares show wells with the Tattoo and Etsho areas. The black polygons show producing fields. Field and well data obtained from the B.C. Oil and Gas Commission, available at http://data.bcogc.opendata.arcgis.com.. Topography data, GTOPO30, US Geological Survey.
sub-parallel N-S trending deep-seated faults within the Etsho and Tattoo areas of the Horn River Basin, with minor secondary NW-SE faulting evident (BC Oil and Gas Commission, 2012), whilst faulting appears to be confined below the lower Fort Simpson shale, extending into the Precambrian basement.

Thirty-eight earthquakes were detected by the regional seismic monitoring network operated by Natural Resources Canada (NRCan) between 8/4/2009 and 13/12/2011. Twenty-one of the earthquakes had magnitudes of 3.0 or greater, and the largest event had a magnitude of 3.8 ML. This event was also felt by workers in the area. The earthquakes occurred in an area where no previous seismicity had been recorded and a report by the BC Oil and Gas Commission (2012) concluded that the earthquakes were caused by fluid injection during hydraulic fracturing in proximity to pre-existing faults.

Hydraulic fracturing operations in the Etsho area took place between February 2007 and July 2011. During this period, over 90 wells were drilled from 14 different locations, with more than 1,600 hydraulic fracturing stages completed. Twenty-seven of the earthquakes detected by NRCan occurred within 10 km of the Etsho area. Seven drilling pads were located within the same area, five of these were conducting hydraulic fracturing operations when events occurred. All seven of the earthquakes detected by NRCan in the Tattoo area occurred within 10 km of wells in which there were hydraulic fracturing operations when the seismicity occurred.

A dense array consisting of 20 seismometers was deployed by the operator in the Etsho area to study the seismicity in greater detail than was possible with NRCan data. This array operated from 16 June to 15 August 2011 and detected 216 earthquakes ranging from magnitude -0.8 to 3.0 ML, with 19 events greater than 2.0 ML. These earthquakes were interpreted to be related to fault movement and the report by the BC Oil and Gas Commission (2012) concluded that magnitudes from 0.5ML to 1.0ML indicate the transition from fracture driven seismicity to seismicity driven by fault movement. The four earthquakes detected by NRCan in the same time period were relocated by the operator using data from the dense array. The results suggested that the earthquakes were located within 200 m of sections of the borehole where hydraulic fracturing took place.

At both Etsho and Tattoo, all 38 NRCan reported events occurred either during a hydraulic fracturing stage or sometime after one stage ended and another began. No events were recorded before hydraulic fracturing operations began or after the last hydraulic fracturing operations ended.

The average volume of fluid injected into wells for hydraulic fracturing in the Etsho area was approximately 60,000 m$^3$, with a maximum of 138,000 m$^3$ and a minimum of 11,000 m$^3$, with corresponding flow rates of 0.2 m$^3$/s, 0.25 m$^3$/s and 0.13 m$^3$/s, respectively.

In British Columbia, the only previously documented case of induced seismicity, linked to oil and gas activity, occurred in the Eagle Field area, approximately five km north of Fort St. John. Twenty-nine earthquakes with magnitudes from 2.2 to 4.3 ML were recorded from November 1984 to May 1994. Horner (1994) used the Davis and Frohlich (1993) criteria to conclude that the events were induced. High pressure fluid injection for secondary oil recovery was identified as a possible cause. High volume hydraulic fracturing was not employed in the area at that time.

### 3.6 EARTHQUAKES IN THE EOLA FIELD, OKLAHOMA,

In January 2011, a sequence of earthquakes occurred in close proximity to a well, which was being hydraulically fractured in the Eola-Robberson oil field, south-central Oklahoma (Holland, 2013). A total of 116 earthquakes were detected by Holland (2013) between 17/01/2011 at 19:06 and 23/01/2011 at 3:13 GMT. Hydraulic fracturing operations in the Picket Unit B Well 4–18 took place between 16/01/2011 at 18:43 and 22/01/2014 at 16:54 GMT. Earthquake magnitudes varied from 0.6 to 2.9 ML, with 16 earthquakes having magnitudes of 2.0 ML or greater. The locations calculated by Holland (2013) suggest that the earthquakes occurred at shallow depths
from 2 to 3 km and within ~2.5 km of the well. The alignment of the hypocentres suggests that the earthquakes occurred on a fault striking N166°E, subparallel to the mapped faults in the area. The first earthquake occurred ~24 hours after hydraulic fracturing began at the well. This delay is consistent with the diffusion of pore pressure in the subsurface over a distance of ~2 km. The strong spatial and temporal correlation between hydraulic fracturing and earthquakes suggests that the earthquakes were induced. This correlation is strengthened because hydraulic fracturing operations ceased for ~2 days due to bad weather, and earthquakes can be observed to cease during this period and resume after hydraulic fracturing had resumed. In addition, no other similar earthquakes were identified at other times before or after hydraulic fracturing.

The Eola-Robberson field lies at the northern edge of the Ardmore Basin, and is part of the Devonian-aged Woodford Shale gas play (Holland, 2013). The Woodford Shale gas play covers virtually the entirety of Oklahoma, and stretches from southern Kansas to west Texas. It is between 15 – 90 m thick, and is found at depths of between 275 and 3960 m (Vulgamore et al., 2007). The field contains a highly folded and faulted thrust system (Holland, 2013), and has undergone numerous phases of tectonic deformation, from initial rifting during the Cambrian (Keller et al., 1983) to transpression (and probable reactivation of Cambrian structures) during the late Carboniferous (Granath, 1989). Numerous major parallel faults trend WNW to ESE, with several NW to SE trending faults intersecting these. The Eola field is block faulted between major faults with a strike-slip component, with fault dips near vertical (Harlton, 1964).

3.7 EARTHQUAKES IN HARRISON COUNTY, OHIO

Friberg et al. (2014) discuss an earthquake sequence detected in Harrison County, Ohio between 7 September and 14 December 2014, and relate it to a hydraulic fracture operation. The sequence consisted of several hundred earthquakes, the largest of which had a magnitude of 2.1 ML. The start and stop of the activity is coincident with the start and stop of hydraulic fracture operations in the nearby Ryser-2, Ryser-3 and Ryser-4 horizontal wells, with some temporal delay. The similarity in the recorded waveforms suggested that the events originated from the same source location and the located earthquakes line up along a steeply dipping east-west trending structure at a depth of 3.2 km immediately beneath the wells. Friberg et al. (2014) conclude that the earthquakes occurred on a fault in the Pre-Cambrian crystalline basement, not in the Palaeozoic formations where the wells were located.

3.8 EARTHQUAKES IN POLAND TOWNSHIP, OHIO

Skoumal et al. (2015) identified 77 earthquakes in Poland Township, Ohio, between 4-12 March, 2014, that were spatially and temporally correlated with active hydraulic fracture operations. The largest earthquake had a magnitude of 3.0 ML and five other events had magnitude of 2.0 ML or above. The earthquakes occurred during hydraulic fracturing of two horizontal wells that were located 0.8 km away and activity decayed after the Ohio Department of Natural Resources issued a shutdown of the hydraulic fracturing. Precise relative locations calculated for the earthquake hypocentres lined up along a vertical plane. The calculated focal mechanism gave a vertical fault plane in good agreement with both the alignment of the hypocenters and with the regional stress field. Skoumal et al. (2015) conclude that the hydraulic fracturing induced slip on a pre-existing fault that was optimally oriented with respect to the regional stress field.

3.9 EARTHQUAKES IN THE MONTNEY TREND, BRITISH COLUMBIA

The Montney Trend is a 29,850 km² siltstone formation that stretches from the British Columbia-Alberta border, near Dawson Creek, 200 km northwest to the Rocky Mountain foothills. It lies at the western edge of the West Canada Sedimentary basin. Unconventional gas development in the Montney began in the mid-2000s, and by 2014 the region had become British Columbia’s most important natural gas producing area. In 2014, the Montney had over 1,700 active natural gas wells.
Natural Resources Canada recorded 231 earthquakes in the Montney Trend between May 2013 and October 2014, with magnitudes from 1.0 to 4.4 Mw. A study by the BC Oil and Gas Commission (2014) found that 193 were correlated in both space and time with hydraulic fracturing operations in the Doe-Dawson, Septimus, Altares, Beg-Town and Caribou gas producing areas. Another 38 earthquakes were found to be correlated with wastewater disposal wells in the Graham and Pintail areas. The maximum injected volume in any stage was approximately 2,200 m$^3$.

The largest event had a magnitude of 4.4 Mw and was located in the Caribou area, approximately 200 km northwest of Fort St. John. A magnitude 4.2 Mw earthquake was recorded on 28 May, 2013, in the Septimus area, 10 km south of Fort St. John.

Figure 3.6. Coloured circles show earthquakes recorded by Natural Resource Canada between May 2013 and end October 2014. The circles are coloured by date. The yellow stars show the locations of the three largest earthquakes in the sequence, with magnitudes of 4.4, 4.2 and 3.8 Mw. The blue shaded areas show the gas producing areas linked to the seismicity, while the small black dots show well positions. The grey squares show towns. Earthquake data from the National Earthquake DataBase (NEDB), compiled by Natural Resources Canada. Well data obtained from the Alberta Energy Regulator, available at https://www.aer.ca/data-and-publications.
No injuries or property damage were linked to the seismicity and the recorded ground motions were below damage thresholds. However, the event triggered an automatic shutdown of a nearby gas plant and precautionary flaring of gas. Several hundred people were without power for a prolonged period. Several instances of casing deformation occurred within the horizontal portion of shale gas wellbores, but no loss of integrity within the wells and no impact on the vertical portions of wellbores. Atkinson et al. (2015) found that high-frequency ground motions were lower than those predicted by ground motion prediction equations commonly used in seismic hazard assessments, possibly as a result of a low stress drop. However, Atkinson et al. (2015) also suggest that moderate-induced earthquakes in the magnitude range 4-5 may be damaging as a result of the expected shallow focal depths.

3.10 CROOKED LAKE, ALBERTA

A sequence of more than 160 earthquakes occurred between November 2013 and December 2014 near Crooked Lake, Alberta, Canada. Schultz et al. (2015) find that the seismicity in the Crooked Lake Sequence is correlated both in space and time with hydraulic fracturing operations in the McKinley and Waskahigan fields, approximately 30 km west of Fox Creek. The largest event in the sequence had a magnitude of 3.8 Mw. Earthquake activity has continued in this region and a magnitude 4.4 earthquake on 12 January 2016, 15 km west-northwest of Fox Creek is also suspected to be due to hydraulic fracturing.

Hydraulic fracturing in the area is used to exploit the Duvernay Formation, an organic-rich shale with an average depth of approximately 3400m. Hydraulic fracturing operations typically consist of multi-staged pressure treatments with average pressures, pump rates and volumes of 60 MPa, 9 m³/min and 2700 m³, respectively.

Figure 3.7. Map showing triggered seismicity west of Fox Creek, Alberta, Canada. The red circles show seismicity recorded by Natural Resources Canada, in the period November 2013 to May 2016. The grey circles show locations calculated for the Crooked Lake sequence between November 2013 and December 2014 by Schultz et al. (2015). Earthquake symbols are scaled by magnitude. Earthquake data from the National Earthquake Data Base (NEDB), compiled by Natural Resources Canada. Topography data, GTOPO30, US Geological Survey.
3.11 RATON BASIN, COLORADO-NEW MEXICO

Coal-bed methane is extracted by direct drilling into a coal seam, which allows both gas and produced water to flow to the surface. Hydraulic fracturing is sometimes used to release gas from a coal seam. Australia, Canada and the United States all have commercial coal bed methane production. In the United States, most CBM production came from the Rocky Mountain States of Colorado, Wyoming, and New Mexico. A number of notable earthquakes have been observed in the Raton Basin, situated along the Colorado–New Mexico border, since coal-bed methane production began there in the 1990’s (Figure 3.8).

The Raton Basin is a coal-bearing sedimentary basin, between the Great Plains to the east and the Rio Grande rift to the west. It is approximately 150 km long and 75 km wide at its maximum. Geological mapping within the Raton Basin reveals little evidence for faulting. The basin is bounded by thrust faults at its western edge and by a west-dipping northwest-striking normal fault along its eastern side. There are few mapped faults within the basin, although Robson and Banta (1987) identified two normal faults in the basin that are buried in the Precambrian basement. These do not outcrop at the surface and there is no evidence that they have been active in the Quaternary period. Similarly, the USGS Quaternary Fault and Fold Database (2016) does not contain any active faults within the basin.

Figure 3.8. Circles show earthquake activity in the Raton Basin (USGS ComCat, 2016). The circles are scaled by magnitude. The two red circles show the magnitude 5 earthquake on 10 August 2005 and the magnitude 5.3 earthquake on 23 August 2011. The grey shaded area shows the extent of the basin (from Coleman and Cahan, 2012).

Coal-bed methane production in the Raton Basin began in 1994 and has continued to present. Production is from the Raton, Vermejo and Trinidad formations, at depths from 200 to 800 m depth. Considerable formation water is produced with the methane some of this is disposed of in deep wells. Wastewater disposal began in Colorado in 1994 and in New Mexico in 1999, with injection primarily in to the Dakota formation (Johnson, 1969), at depths between 1250 and 2100 m. Figure 3.9 shows how earthquake activity has increased following the start of coal-bed methane production.
Rubinstein et al. (2014) investigated seismicity in the Raton basin from 1972 to 2013 and conclude that the disposal of wastewater from the coal-bed methane field in deep injection wells is responsible for inducing the majority of the seismicity since 2001. Evidence for this includes a major increase in seismicity shortly after major wastewater injection began in 1999 and the fact that most of the seismicity lies within 5 km for active wells and is at a shallow depth. Also, both the volume of injected water and the injection rates are high.

There have been three notable sequences of seismicity since 2001: August-September 2001; August-September 2005; and August-September 2011. The August-September 2005 sequence included a magnitude 5 earthquake, while the August-September 2011 sequence included a magnitude 5.3 event, the largest recorded earthquake in the area. Earthquakes within the 2001 and 2011 sequences lie within 2 km of high volume injection wells. Two wells adjacent to the magnitude 5.3 earthquake in August 2011 injected 4.9 million cubic meters of wastewater prior to the earthquake.

Figure 3.9. Cumulative number of earthquakes in the Raton Basin with magnitudes greater than 3 as a function of time. Activity increases dramatically shortly after the start of coal-bed methane production (after Rubinstein et al., 2014). Earthquake data from the U.S. Geological Survey (USGS) ComCat

3.12 INDUCED SEISMICITY AND WASTEWATER DISPOSAL

There is mounting evidence that the disposal of the wastewater related to oil and gas production in Class II Underground Injection Control (UIC) wells can lead to increases in observed seismicity rates and damaging earthquakes. Ellsworth (2013) shows that that numbers of earthquakes in central and eastern U.S. have increased dramatically in the last few years. This is demonstrated in Figure 3.10, which shows that 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. In addition, several of the largest earthquakes in the U.S. midcontinent in the last few years may have been triggered by nearby disposal wells, and of the seven earthquakes of magnitude 4.0 or greater that occurred east of the Rocky mountains, six are thought to have been induced. The magnitude 4.0 Mw earthquake on 31 December 2011 in Youngstown, Ohio, appears to have been induced by the disposal of wastewater in a UIC well at depths of up to 3.0 km (Kim, 2013).
The magnitude 4.7 earthquake in central Arkansas in 2011 has also been linked to disposal of wastewater in a UIC well at depths of 2-3 km (Horton, 2012). The magnitude 4.4 Mw earthquake on 11 September 2011, near Snyder, Texas, occurred in an oil field where injection for secondary recovery has been inducing earthquakes for years (Davis and Pennington, 1989). The largest of these was a magnitude 5.7 earthquake in Prague, central Oklahoma that was located close to active UIC wells, which destroyed 14 homes and injured two people (Kerenan et al., 2013).

Figure 3.10. Cumulative count of earthquakes with M ≥ 3 in the central and eastern United States, 1967–2012 (after Ellsworth, 2013). Earthquake data from the U.S. Geological Survey (USGS) ComCat

These results provide a significant body of evidence that wastewater disposal by injection into UIC wells poses a significant seismic risk. The report by the National Research Council in the U.S.A. (NAS, 2012), which examined the scale, scope and consequences of seismicity induced during fluid injection and withdrawal related to energy technologies, concluded that injection for disposal of wastewater derived from energy technologies into the subsurface does pose some risk for induced seismicity, but very few events have been documented over the past several decades relative to the large number of disposal wells in operation.

Figure 3.11 shows a USGS map showing the wastewater injection wells in Central and Eastern US that have (red) and have not (grey) been associated with earthquakes. The fluid injection wells associated with earthquakes are defined as being within a 15 km radius and active at the time of an earthquake. Named areas that have been impacted by these induced earthquakes are delineated by the polygons. This shows that although many wells can be associated with
earthquakes, the majority are not. Rubinstein et al. (2015) state that while there are approximately 35,000 active wastewater disposal wells and 80,000 active enhanced oil-recovery wells in the United States, only a very small number of these are known to have induced felt earthquakes. Factors controlling the occurrence of earthquakes are likely to include the size and state of stress of nearby faults as well as fluid pressure changes that are large enough to induce earthquakes.

Some of the wastewater injected into UIC wells comes from hydraulic fracturing used in unconventional oil and gas production, while some is produced water from conventional hydrocarbon production. Produced water is the salty brine that is held in the same pore space as oil and gas and is extracted at the same time at nearly all oil wells. The nature of the wastewater varies from place to place. For example, the fluids disposed of near earthquake sequences in Youngstown, Ohio (Horton, 2012), and Guy, Arkansas (Kim, 2013), are believed to consist largely of spent hydraulic fracturing fluid, whereas the vast majority of the fluid that is injected in disposal wells in Oklahoma is produced water (Murray, 2013).

![Figure 3.11. USGS map displaying 21 areas impacted by induced earthquakes as well as the location of fluid injection wells that have and have not been associated with earthquakes. Credit: U.S. Geological Survey, Open-File Report OFR-2016-1035](image)

As a result of this, the USGS has recently produced a 1-year seismic hazard forecast for the Central and Eastern United States (CEUS) that includes contributions from both induced and natural earthquakes. Conversion of ground shaking to seismic intensity (Figure 3.12) indicates that some places in Oklahoma, Kansas, Colorado, New Mexico, Texas, and Arkansas may experience damage if the induced seismicity continues unabated. The chance of having Modified Mercalli Intensity (MMI) VI or greater (damaging earthquake shaking) is 5–12 percent per year in north-central Oklahoma and southern Kansas, similar to the chance of damage caused by natural earthquakes at sites in parts of California.
Figure 3.12. USGS map displaying the intensity of potential ground shaking with a 1% probability of being exceeded in one year. Both natural and human induced earthquakes are included. Credit: U.S. Geological Survey, U.S.G.S. Open-File Report OFR-2016-1035

3.13 DISCUSSION

The process of hydraulic fracturing a well, as presently implemented for shale gas recovery, is generally considered to pose a low risk of inducing either felt, damaging or destructive earthquakes (e.g. NAS, 2012; Royal Society, 2012). Although hydraulic fracturing is generally accompanied by microseismicity, the magnitudes of these events are usually less than 2.0 making them too small to be felt by people. Given the large number of stimulations that have been carried out in in the US and Canada and the small number of felt earthquakes, the probability of felt earthquakes appears to be very small.

There are at least seven documented examples of earthquakes with magnitudes greater than two that have been conclusively linked to hydraulic fracturing for shale gas exploration/recovery. Seismicity is most notable in Canada, where a magnitude of 4.4 Mw near Fort St John in August 2014 is largest known earthquake suspected to have been induced by hydraulic fracture operations in a hydrocarbon field anywhere in the world. This event resulted in an automatic shutdown of a nearby gas plant and precautionary flaring of gas. Felt seismicity associated with hydraulic fracturing of the Preese Hall well near Blackpool in 2011 led to the suspension of all such operations in the UK for several years. In this case, the magnitudes of the observed earthquakes were relatively small, with only one event in the sequence of over 50 exceeding a magnitude of 2.0 ML.
The mechanism for these larger earthquakes is generally well-understood and is constrained by observations and modelling. Fluids injected during the hydraulic fracturing process can change the stress conditions on pre-existing faults making it easier for them to slip. This can happen because the injected fluid increases the pore fluid pressure on the fault, which reduces the frictional resistance and makes it easier for the fault to slip. The reactivation potential of a fault depends both on the existing stress field and magnitude of the stress change caused by the injected fluid. If a fault is close to failure it may only require a small stress perturbation to cause it to slip. The energy released in larger induced events is a result of the long term accumulation of strain rather than the energy from the injected fluid. As a result maximum magnitudes for such induced earthquakes will be similar to those for tectonic earthquakes in the region.

Figure 3.13. Earthquakes in the Western Canada Sedimentary basin (WCSB) with a magnitude of 3.0 or above (after Atkinson et al. (2016). The boxes delineate an area parallel to the foothills of the Rockies where induced seismicity has been observed. Earthquake data from the National Earthquake DataBase (NEDB), compiled by Natural Resources Canada. Topography data, GTOPO30, US Geological Survey.

There is a significant contrast between experience in central United States and Canada. In the central United States, most induced seismicity is linked to disposal of co-produced wastewater from oil and gas extraction (Ellsworth, 2013). Atkinson et al. (2016) suggest that most recent cases of induced seismicity in western Canada are highly correlated in space and time with hydraulic fracturing, and state that the observed maximum magnitude of events associated with
hydraulic fracturing appears to exceed the predictions of the McGarr (2014) relationship between the volume of injected fluid and the maximum expected magnitude.

Figure 3.13 shows earthquakes in the Western Canada Sedimentary basin (WCSB) with a magnitude of 3.0 or above (after Atkinson et al., 2016) for the time period 1985-2015. The boxes delineate an area parallel to the foothills of the Rockies where induced seismicity has been observed. Figure 3.13 shows the cumulative number of events as a function of time for the same data as shown in Figure 3.13. It is clear that between 1985 and 2005, the number of earthquakes increases at a constant rate, whereas after 2005 it starts to increase at a greater rate and this corresponds to the increase in the number of hydraulically fractured wells.

The difference in response to hydraulic fracturing in the US and Canada is not well understood. It may be related to higher background seismicity rates in British Columbia and western Alberta, however, this remains speculative. In the time period from 1985 to 2005 there were 99 earthquakes with a magnitude of 3 or greater in the area of interest shown in Figure 3.13, and, assuming that the catalogue is complete for events of this magnitude and above in this time period, this corresponds to an annual rate of 4.95. Taking into account the area of the zone of interest (465,963 km²) gives a scaled seismicity rate of 7.93×10⁻⁶/km², which is almost three times the value calculated for Texas (2.54×10⁻⁶/km²) and twice the value calculated for Scotland (4.94×10⁻⁶/km²).

It is likely that an earthquake similar in magnitude to the largest events linked to hydraulic fracturing in the West Canada Sedimentary Basin (4.4 MW) would be strongly felt across much of the Midland Valley of Scotland and could even cause some superficial damage. However, earthquakes with magnitudes similar to those observed in Blackpool and Garvin County would be unlikely to cause any damage, although they could be felt by people close to the epicentre and may cause some concern to the local population.

![Figure 3.14](image-url)

Figure 3.14. Cumulative number of earthquakes with a magnitude of 3.0 or above (blue squares) within the parts of the WCSB in the area delineated by the rectangles in Figure 3.13 from 1985 to 2015 (after Atkinson at al, 2016). The blue line shows the increase in number of hydraulically fractured wells. Earthquake data from the National Earthquake Data Base (NEDB), compiled by Natural Resources Canada. Well data obtained from the Alberta Energy Regulator and the B.C. Oil and Gas Commission, available at [https://www.aer.ca/data-and-publications](https://www.aer.ca/data-and-publications) and [http://data.bcogc.opendata.arcgis.com](http://data.bcogc.opendata.arcgis.com).

Studies of earthquake activity in the Raton Basin (Rubinstein et al, 2014) an area that has produced coal-bed methane since 1994, provides strong evidence that a this activity is related to
the subsequent disposal of wastewater from the coal-bed methane extraction process by injection into deep wells, rather than from the extraction process itself. Literature was not located concerning induced seismicity and coal-bed methane extraction in Canada, Australia or other parts of the USA, suggesting that this is not a major issue in those areas.

The observed increases in earthquake rates and significant earthquakes in many areas of the Central and Eastern United States, which have been linked to the disposal of wastewater by injection into UIC wells (Ellsworth, 2013; Keranen et al., 2014; Weingarten et al., 2015), provide a considerable body of evidence that this activity has a non-negligible contribution to the seismic hazard. Previous National Seismic Hazard Models (NSHM) for the United States published by the USGS (e.g. Petersen et al., 2014) did not consider non-tectonic events. However, Petersen et al. (2016) have now published 1-year seismic hazard forecast for 2016 for the Central and Eastern United States (CEUS) that includes contributions from both induced and natural earthquakes. This forecast shows increases in earthquake hazard by a factor of 3 or more in some areas of induced earthquake activity. In areas where induced activity appears to have stopped seismic hazard returns to the 2014 result. Petersen et al. (2016) suggest that some places in Oklahoma, Kansas, Colorado, New Mexico, Texas, and Arkansas may experience damage if the induced seismicity continues unabated. The chance of having Modified Mercalli Intensity (MMI) VI or greater (damaging earthquake shaking) is 5–12 percent per year in north-central Oklahoma and southern Kansas, similar to the chance of damage caused by natural earthquakes at sites in parts of California.

Of the considered case studies, the Bowland Basin (Blackpool) is the most geologically similar to the Midland Valley of Scotland and is also on a similar physical scale to the Midland Valley of Scotland, unlike the US and Canadian examples which are at least twice the size. For example, the Barnett Shale in the Fort Worth Basin (Texas) extends for 72,000 km², whilst the Midland Valley covers around 7,000 km².

The Midland Valley and the Bowland Basin are around 1,500 km from the nearest plate boundary (the Mid-Atlantic Ridge). The Horn River Basin is less than 1,000 km from the subducting margin of the Pacific Plate. While Oklahoma and Texas are also far from any plate boundaries, the Eola-Robberson field (Oklahoma) has a complex tectonic history with a faulted thrust system, and the Fort Worth (Texas) Basin is bordered on its south-east side by a major thrust front.

Both the Midland Valley and the Bowland Basin have unconventional targets in Carboniferous rocks, and both have a similar NE-SW or ENE-WSW dominant structural grain. However, the prospective shale resource in the Bowland Basin consists of thick deposits of shale deposited in a deep marine setting (Andrews, 2013), whilst the shales in the Midland Valley were deposited in a lacustrine, fluvio-deltaic and shallow marine depositional environment and are intercalated in a stacked sequence with numerous relatively thin shales (Monaghan, 2014). Many of the US gas shales were also deposited in a deep marine setting, e.g. the shales in the Fort Worth Basin were deposited in a deep foreland basin (Bruner and Smosna, 2011). In general, the UK shale targets are thicker than their American counterparts.

The faults that cut the Carboniferous strata in the Midland Valley are mapped at surface, whereas the faults that cut the shales in the Horn River Basin do not penetrate the surface and are hidden by an overlying clay-rich mudstone above the prospective organic-shale units. The faults that cut the Midland Valley and Bowland Basin are mostly normal, with a component of strike-slip and reverse, and were last active during the late-Carboniferous to early-Permian. Conversely, the Eola field in Oklahoma is dominated by transpressional strike-slip faulting and thrusts (Kilic and Tapp, 2014).

No major faults intersect the Midland Valley of Scotland, unlike the Horn River Basin, which is cut by the 200 km long Bovie Fault, which was last active during the Cretaceous. The faults which cut the Barnett Shale are mostly associated with the Oachita Thrust front or basement structures (Walper, 1982; Montgomery et al., 2005), but may also be associated with dissolution
of the underlying karstic Ellenburger Group (Gale et al., 2007): there is no such thrust control to the structure of the Midland Valley nor a comparable underlying karstic unit.
4 Statutory and Non-statutory frameworks for monitoring and mitigating seismic activity

4.1 OVERVIEW

Recently published regulations for onshore oil and gas (shale gas) exploration in the UK (DECC, 2013) contain specific measures for the mitigation of induced seismicity including: avoiding faults during hydraulic fracturing; assessing baseline levels of earthquake activity; monitoring seismic activity during and after fracturing; and, using a ‘traffic light’ system that controls whether injection can proceed or not, based on that seismic activity. Regulatory measures to mitigate the risk of induced seismicity are also in place in the US, Canada. In the US, much of this regulation is aimed at induced seismicity related to wastewater disposal in UIC wells, although this is also relevant to induced seismicity from hydraulic fracturing. These measures are broadly similar to those specified by DECC. The magnitude limit set by DECC for the cessation of hydraulic fracturing operations (0.5 ML) is considerably less than the limits in California (2.7 ML) and Illinois, Alberta and British Columbia (4.0 ML), and may be considered a conservative threshold. Local monitoring systems that are capable of reliable measurement of earthquakes with very small magnitudes will be required to implement this limit successfully.

4.2 MEASURES FOR MITIGATION OF SEISMIC RISK

There are relatively few published measures for mitigation of seismic risk from hydraulic fracturing operations in unconventional hydrocarbon reservoirs. This is keeping with the limited number of examples of earthquakes that have been large enough to be felt that were induced by hydraulic fracturing for UOG, and the supposed low risk of the process inducing destructive earthquakes (NAS, 2012). Extensive experience of induced seismicity in Enhanced Geothermal Systems has led to a series of measures to address induce seismicity that is often considered as “industry best practice”. For example, the U.S. Department of Energy “Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems” (Majer et al., 2012) list seven steps for mitigating seismic risk. These are listed in Table 4.1 and include establishment of seismic monitoring and quantifying the hazard from natural and induced seismic events.

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Perform a preliminary screening evaluation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 2</td>
<td>Implement an outreach and communication program.</td>
</tr>
<tr>
<td>Step 3</td>
<td>Review and select criteria for ground vibration and noise.</td>
</tr>
<tr>
<td>Step 4</td>
<td>Establish seismic monitoring.</td>
</tr>
<tr>
<td>Step 5</td>
<td>Quantify the hazard from natural and induced seismic events.</td>
</tr>
<tr>
<td>Step 6</td>
<td>Characterize the risk of induced seismic events.</td>
</tr>
<tr>
<td>Step 7</td>
<td>Develop risk-based mitigation plan.</td>
</tr>
</tbody>
</table>

Table 4.1. The U.S. Department of Energy Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems (Steps are listed in the order expected to be followed). Adapted from Majer et al. (2012).

Majer et al. (2012) make the following four recommendations for baseline monitoring in the geothermal industry.

1. Monitoring needs to fully characterise background seismic activity and identify any faults with the potential to be affected by operations, and should not be biased in time or space in the vicinity of the potential geothermal project. The duration of the background monitoring may be relatively short (one month) if there is already existing monitoring...
that can detect small earthquakes with magnitude around 1. If there is no existing monitoring, the duration may need to be extended for as long as six months.

2. High resolution instrumentation will allow induced activity to be modelled and forecast more accurately. As the induced earthquakes may span several orders of magnitude, say from -2 to 4, the monitoring system requires a high dynamic range to ensure that data of sufficient quality is recorded. Also, borehole installations are better than surface sensors as the signal-to-noise ratio is better, and this allows smaller events to be recorded, increasing resolution and location capability. The monitoring network should be able to provide comprehensive background monitoring over an area at least twice as large as the area of geothermal potential.

3. Data processing must provide locations, magnitudes and source mechanisms. A typical geothermal project, consisting of one or two injection wells and several production wells in an area with a diameter of 5 km, will require at least eight monitoring stations distributed over the area of interest.

4. Monitoring should be maintained throughout the injection activity to validate the engineering design of the injection in terms of fluid movement directions, and to guide the operators on optimal injection volumes and rates. This will also allow induced events to be discriminated from natural seismicity and ensure that local vibration guidelines are being followed.

Experience of induced seismic activity in Enhanced Geothermal Systems (EGS) has also led to the development of ‘traffic light systems’ linked to real-time monitoring of seismic activity (e.g. Bommer et al., 2006; Majer et al., 2012). These are essentially control systems for management of induced seismicity that allow for low levels of seismicity but add requirements when seismic events may result in a concern for public health and safety. For example, Table 4.2 shows the traffic light system used in Basel, Switzerland and adapted from Bommer et al. (2006). This has four levels: green, where injection proceeds as planned; yellow/orange, injection proceeds with caution, possibly at a reduced rate; and, red, injection is suspended immediately.

<table>
<thead>
<tr>
<th>Traffic Light</th>
<th>Earthquake Activity</th>
<th>Earthquake Magnitude</th>
<th>Ground Velocity</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>None</td>
<td>ML &lt; 2.3</td>
<td>&lt; 0.5 mm/s</td>
<td>Regular operation. Continue pumping.</td>
</tr>
<tr>
<td>Yellow</td>
<td>Some</td>
<td>ML ≥ 2.3</td>
<td>≤ 2.0 mm/s</td>
<td>Continue pumping but do not increase flow rate</td>
</tr>
<tr>
<td>Orange</td>
<td>Many</td>
<td>ML ≤ 2.9</td>
<td>≤ 5.0 mm/s</td>
<td>Maintain well head pressure below stimulation pressure</td>
</tr>
<tr>
<td>Red</td>
<td>Widely Felt</td>
<td>ML &gt; 2.9</td>
<td>&gt; 5 mm/s</td>
<td>Stop pumping. Bleed off to minimum wellhead pressure</td>
</tr>
</tbody>
</table>

Table 4.2. Seismic response procedure used in Basel, Switzerland (and adapted from the traffic light system proposed by Bommer et al. (2006). The system is based on three independent parameters: (1) public response; (2) local magnitude (ML); and, peak ground velocity (PGV))

Any traffic light system requires the definition of acceptable limits for the cessation and recommencement of operations. These limits are generally based on levels of ground motion which may represent a hazard or a public nuisance. In some cases, the cessation of operations at a given limit may not be sufficient to preclude further seismicity. For example, in the case of Basel, 2006 (Giardini, 2009), operations were stopped when the traffic light threshold of 2.9 ML was exceeded, but this was still followed by a number of larger magnitude events. Bachmann et al. (2011) present an alternative probability based statistical approach that is used to describe and forecast features of the observed induced seismicity at Basel in 2006. This approach has the
advantage of not being dependent on a single magnitude threshold but on many small events, which increases robustness. It also integrates injection rates and allows forecasts of the hazard/risk to be made.

In addition, an effective traffic light system depends on a real-time seismic monitoring system that can provide reliable automatic locations and magnitudes for events that are at least one or two orders of magnitude smaller than the lowest specified limit. For conservative thresholds, this may require accurate determination of source parameters for very small events with magnitudes of -1 ML or even less. Sensors may need to be deployed in boreholes to achieve this. Site specific monitoring systems in the geothermal industry often consist of several three-component sensors (geophones or accelerometers) installed in boreholes surrounding the volume of rock to be stimulated, at distances of 100 m to 10 km from the injection well. The sensors are generally placed at a range of depths (~100 - 2000m) with those sensors at greater depths designed to withstand high temperatures and pressures.

4.3 REGULATION IN THE UK

Following the induced seismicity near Blackpool, UK in 2011, the UK Department for Energy and Climate Change (DECC) published a regulatory roadmap\(^3\) to provide an indicative overview of the permitting and permissions process for exploratory work in oil and gas development, onshore in the UK, and to help operators understand the regulation process for onshore oil and gas (shale gas) exploration in the UK. The roadmap outlines the numerous steps, permitting and permissions required for exploratory work for onshore oil and gas development to proceed, from the award of the Petroleum and Exploration Development License (PEDL) through to well testing post drilling. Once a consent to drill has been granted (following the award of relevant permits and notification of all relevant consultees), the operator is responsible for the formulation of an outline ‘Hydraulic Fracture Plan’, to be agreed by DECC. The Hydraulic Fracture Plan must ‘establish arrangements to control seismicity and provide a detailed plan for monitoring hydraulic fracturing operations’ (DECC, 2013), achieved in part by the agreement of an appropriate ‘traffic light’ system. Following the approval of the Hydraulic Fracture Plan, DECC will then grant the operator the right to start hydraulic fracturing operations. The specific measures for the mitigation of induced seismicity are summarised in Table 4.3.

<table>
<thead>
<tr>
<th></th>
<th>Use all available geological information to assess the location of faults before wells are drilled to avoid hydraulically fracturing near faults</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Use British Geological Survey records to assess baseline levels for seismic activity (vibrations of the earth’s crust)</td>
</tr>
<tr>
<td>3</td>
<td>Inject as little fluid as necessary into the rock during fracturing</td>
</tr>
<tr>
<td>4</td>
<td>Monitor seismic activity during and after fracturing</td>
</tr>
<tr>
<td>5</td>
<td>Adopt a ‘traffic light’ system that controls whether injection can proceed or not, based on that seismic activity</td>
</tr>
</tbody>
</table>

Table 4.3. Measures for the mitigation of induced seismicity set out in the DECC regulatory roadmap.

Green et al. (2012) suggest that 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, is also likely to reduce the probability of significant earthquakes.

The DECC traffic light threshold for the cessation of hydraulic fracturing operations is 0.5 ML. An event of this magnitude is unlikely to be felt and does not pose any seismic hazard. It would only be detected by sensitive monitoring equipment in the vicinity of the epicentre.

United Kingdom Onshore Oil and Gas (UKOOG), the representative body for the UK onshore oil and gas industry, has also published guidelines for onshore shale gas wells in the UK\(^4\). These contain what is considered to be good industry practice and reference the relevant legislation, standards and practices. A key part of this process is that operators should develop a Hydraulic Fracturing Programme (HFP), following a risk-based approach, that describes the control and mitigation measures for fracture containment and for any potential induced seismicity.

4.4 CANADA

In 2015, following seismicity in the Fox Creek area, the Alberta Energy Regulator (AER) issued Subsurface Order No. 2\(^5\). This order specifies requirements in relation to hydraulic fracture operations in wells within the Duvernay Zones. These include the following:

a) Assess the potential for induced seismicity and be immediately prepared to implement a plan to monitor for, mitigate, and respond to induced seismicity
b) Seismic monitoring conducted by or on behalf of the licensee pursuant to this order must be sufficient to detect a 2.0 ML seismic event within 5 km of any affected well.
c) Report any seismic events of 2.0 or above within 5 km of any affected well.
d) In the case of such an event, licensees must implement the induced seismicity plan to eliminate or reduce further seismic events caused by or resulting from hydraulic fracturing operations.
e) Immediately cease hydraulic fracturing operations if there are any seismic events of magnitude 4.0 ML or greater within 5 km of the affected well.
f) Suspended hydraulic fracturing operations may only be recommenced with written consent of the AER.

Similarly, following the seismicity associated with hydraulic fracturing in the Horn River area, the British Columbia Oil and Gas Commission (2012) published a number of recommendations for the mitigation of seismic risk in future hydraulic fracture operations for shale gas. These are listed in Table 4.4.

<table>
<thead>
<tr>
<th></th>
<th>Improve the accuracy of the Canadian National Seismograph Network in northeast B.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Perform geological and seismic assessments to identify pre-existing faulting.</td>
</tr>
<tr>
<td>3</td>
<td>Establish induced seismicity monitoring and reporting. Suspend operations on detection of a 4.0 ML or greater event</td>
</tr>
<tr>
<td>4</td>
<td>Install ground motion sensors to quantify risk from ground motion</td>
</tr>
<tr>
<td>5</td>
<td>Characterisation of any possible active faults in the region using all available data.</td>
</tr>
<tr>
<td>6</td>
<td>Submission of micro-seismic reports to monitor hydraulic fracturing for containment of micro fracturing and to identify existing faults</td>
</tr>
</tbody>
</table>

**Table 4.4. Recommendations Investigation of Observed Seismicity in the Horn River Basin (BC Oil and Gas Commission, 2012)**

In addition, governments in all jurisdictions are increasing their monitoring of earthquakes, in cooperation with other jurisdictions, universities and stakeholders.

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\(^4\) [http://www.ukoog.org.uk/onshore-extraction/industry-guidelines](http://www.ukoog.org.uk/onshore-extraction/industry-guidelines)

\(^5\) [https://aer.ca/documents/orders/subsurface-orders/SO2.pdf](https://aer.ca/documents/orders/subsurface-orders/SO2.pdf)
4.5 UNITED STATES

There is no federal law whose primary purpose is to reduce the risk of seismic activity associated with fluid withdrawals or injections. States generally have the leading role in regulating shale gas development activities and regulation varies from state to state. While much of this regulation is aimed towards induced seismicity related to wastewater disposal in Class II Underground Injection Control (UIC) wells, much of this is also relevant to induced seismicity from hydraulic fracturing. Class II UIC wells are used specifically to inject oil and gas exploration and production waste for disposal, and for enhanced oil recovery through injection of water, gas, or other substances.

4.5.1 California

The California Code of Regulations section 1785.1 “Monitoring and Evaluation of Seismic Activity in the Vicinity of Hydraulic Fracturing” (2015) states the following:

(a) From commencement of hydraulic fracturing until 10 days after the end of hydraulic fracturing, the operator shall monitor the California Integrated Seismic Network for indication of an earthquake of magnitude 2.7 or greater occurring within a radius of five times the ADSA.6

(b) If an earthquake of magnitude 2.7 or greater is identified under subdivision (a), then the following requirements shall apply:

(1) The operator shall immediately notify the Division7 and inform the Division when the earthquake occurred relative to the hydraulic fracturing operations.

(2) The Division, in consultation with the operator and the California Geological Survey, will conduct an evaluation of the following:

(A) Whether there is indication of a causal connection between the hydraulic fracturing and the earthquake;

(B) Whether there is a pattern of seismic activity in the area that correlates with nearby hydraulic fracturing; and

(C) Whether the mechanical integrity of any active well within the radius specified in subdivision (a) has been compromised.

(3) No further hydraulic fracturing shall be done within the radius specified in subdivision (a) until the Division has completed the evaluation under subdivision (b)(2) and is satisfied that hydraulic fracturing within that radius does not create a heightened risk of seismic activity.

4.5.2 Colorado

The Colorado Oil and Gas Conservation Commission (COGCC), part of the Department of Natural Resources, permits and regulates Class II UIC wells.8 The UIC permit review includes a review for seismicity, using Colorado Geological Survey (CGS) geologic maps, the United States Geological Survey earthquake database, and area-specific knowledge to assess seismic potential. If historical seismicity has been identified in the vicinity of a proposed Class II UIC well, COGCC requires an operator to define the seismicity potential and the proximity to faults through geologic and geophysical data prior to any permit approval. The COGCC also designates a maximum surface injection pressure in order to minimize the potential for seismic events related to fluid injection.

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6 ADSA: Axial Dimensional Stimulation area, which is defined to mean the maximum length, width, height, and azimuth, of the area(s) stimulated by a well stimulation treatment

7 Division of Oil, Gas and Geothermal Resources (DOGGR)

8 https://cogcc.state.co.us/documents/about/TF_Summaries/GovTaskForceSummary_Engineering%20UIC%20Wells.pdf
4.5.3 Illinois

Regulations\textsuperscript{9} state that when an identified well is suspected of triggering induced seismic activity, the permittee must consult with the Illinois Department of Natural Resources (IDNR) and the Illinois State Geological Survey (ISGS) to develop a plan for seismic monitoring, that includes the possibility of new monitoring stations in the vicinity of the well and reduction in rate or pressures of fluid injected. A traffic light system is also in place that allows low levels of seismicity but additional monitoring and mitigation requirements when seismic events are of sufficient intensity to result in a concern for public health and safety.

Illinois DNR must order any operator of a Class II injection well to cease operations immediately if conditions “create imminent danger to the health and safety of the public, or significant damage to property” under any of the following conditions:

1. If an identified well receives a third Yellow Light Alert and within the last year the same permittee received a Notice of Violation for the same well related to flow, pressure or mechanical integrity;
2. If an identified well receives any number of Yellow Light Alerts and there is confirmed property damage to a building or structure as a result of the earthquake event with a magnitude greater than 4.5.
3. If an identified well regulated by this Section receives a fifth Yellow Light Alert.
4. If an identified well receives a Red Light Alert and is within 6 miles of the epicenter of the earthquake event measured from the surface above the hypocenter.

A Red Light Alert is issued to all operators of Class II UIC disposal wells located within 10 miles of the epicenter of an earthquake of magnitude 4.0 or greater.

Yellow Light Alerts are issued by IDNR to all operators of UIC Class II disposal wells located within 6 miles of the epicenter of a seismic event with a magnitude between 2.0 and 4.0. If an operator receives three Yellow Light Alerts within a one-year period, they must immediately reduce injection rates and consult with IDNR and ISGS.

4.5.4 Kansas

A state action plan for induced seismicity was published in 2015. This included the following recommendation and proposals:

1. The state should fund a permanent network of seismometers that would allow earthquakes with a magnitude of 1.5 or greater to be detected and located.
2. The state should fund a portable seismic array that could be deployed to areas experiencing seismic activity in order to obtain more detailed information regarding seismic events.
3. A formula for giving a numerical score to seismic events based on various criteria. Scores above a certain number should prompt regulators to increase monitoring and evaluate whether other regulatory steps are appropriate for a particular injection well or area.

An order issued by the Kansas Corporation Commission in 2015 requires operators of injection disposal wells located in certain areas to measure daily injection volumes and pressures, and to report each month on the daily figures for the prior month.

4.5.5 Ohio

The Ohio Department of Natural Resources Division of Oil and Gas Resources regulates oil and gas activity and Class II injection wells. After the Youngstown earthquakes in 2011 (Horton, 2012), the Department revised its rules regarding injection disposal to address the threat of

\textsuperscript{9} Illinois Administrative Code, Section 240.796, Operating and Reporting Requirements, Hydraulic Fracturing Operations, Seismicity
induced seismicity. Regulation regarding permits for injection disposal\textsuperscript{10} states that the Division of Oil and Gas Resources may require that the operator of an existing well to carry out pressure fall-off tests, investigation of potential faulting within the immediate vicinity of the proposed site, tracer or spinner surveys, and various logs. The Division also may require the operator to submit a plan for seismic monitoring. In addition, the Division may require that the Operator cease operations while the Division is evaluating submitted information. The regulations also give the Division the authority to “implement graduated maximum allowable injection pressure requirements based upon data provided”.

Regulation regarding operation of injection disposal wells\textsuperscript{11} states that all new injection wells must be continuously monitored using an acceptable method and that operators must install a device that will automatically shut off the injection well if injection pressures exceed the maximum pressure allowed by the permit for that well.

4.5.6 Oklahoma

Oil and gas activity and Class II injection wells are regulated by the Oklahoma Corporation Commission, Oil and Gas Division. Regulations\textsuperscript{12} require that operators of injection disposal wells record injection volumes and pressures on a monthly basis. Additionally, for injection into the Arbuckle Formation, the state’s deepest injection formation, operators must monitor and record injection volumes and pressures on a daily basis, keep the records for at least three years, and provide the records to the Commission upon request. The Commission considers such factors as seismicity in the area around the proposed well site and the proximity of the site to faults as part of the permitting process.

In areas of specific interest, the Commission requires operators to record injection volumes and pressures daily. These areas are defined as:

1. All locations within 10 km of the epicenter of an earthquake with a magnitude of 4.0 or greater.
2. All locations within 10 km of an earthquake swarm. Where a swarm is defined as an area consisting of at least two events with epicentres within 0.25 miles of one another and at least one event with a magnitude 3.0 or above.
3. All locations within three miles of a stressed fault, whether or not there has been seismic activity.

4.5.7 Texas

The Railroad Commission regulates oil and gas activity and Class II injection wells. Existing fluid injection regulations were recently revised in order to address and minimize the risk of induced seismicity. The amended Texas Administrative Code states that:

1. Applications for a permit for a new injection well to dispose of saltwater or other oil and gas waste must include USGS information on historical earthquake activity in a 100-square-mile area around the proposed injection site.
2. The Commission has the authority to modify, suspend, or terminate a disposal well permit if scientific data indicates that a disposal well has been determined to be contributing to seismic activity or is likely to be determined to be contributing to seismic activity.
3. The Commission can require operators to report injection volumes and pressures on a more frequent basis than the annual basis otherwise required if conditions exist that increase the risk that fluids will not be contained in the ‘injection interval’ and

\textsuperscript{10} Ohio Administrative Code 1501:9-3-06
\textsuperscript{11} Ohio Administrative Code 1501:9-3-07
\textsuperscript{12} Oklahoma Administrative Code Section 165:10-5-7(c)(3)
4. The Commission can require an applicant for a new injection permit submit information not otherwise required for a permit application if the location proposed for the well is one where conditions exist that increase the risk of non-containment.

4.6 DISCUSSION

Both the DECC and BC Oil and Gas Commission measures make it clear that avoiding injection into active fault zones and faults in brittle rock is likely to reduce the possibility of significant induced seismicity. However, identifying such faults may require a more accurate model of the sub-surface geology than is presently available in some areas. In the case of the Blackpool induced earthquakes in 2011, detailed 3D seismic reflection data was was not available in the vicinity of the well at the time of drilling/well stimulation.

Reviews of historical seismicity are required in many places where hydraulic fracturing operations are ongoing or planned, including the UK, Canada, Colorado, Oklahoma and Texas. The quantity and quality of information will vary depending on a number of factors such as previous monitoring and research. It is important to note that existing catalogues may be limited and the completeness will decrease with magnitude and with time. This may limit the amount of detail on the spatial variation of smaller earthquakes.

It is widely recognised that seismic monitoring is required for monitoring seismic activity during hydraulic fracture operations and as an essential part of any traffic light system. There are no accepted best practice guidelines on how this should be done in terms of numbers or types of sensors, although, for example, the AER state that any seismic monitoring must be sufficient to detect a 2.0 ML seismic event within 5 km of an affected well, which does place some constraint on any network of monitoring sensors.

In the UK, limit for the cessation of hydraulic fracturing operations (0.5 ML) is considerably less than the limits for California (2.7) and Illinois, Alberta and British Columbia (4.0). The detection of earthquakes with a limit of 0.5 ML requires suitably sensitive monitoring networks to be deployed near to active sites during and following hydraulic fracturing. Improved monitoring and measurement at much lower levels will be required to implement such a system successfully. By contrast, a magnitude limit of 4.0 would mean that events near the upper limit would be strongly felt in areas of higher population density such as the Midland Valley of Scotland.

The National Research Council in the U.S. (NAS, 2012) compiled a list of questions (Figure 4.1) that can be used to understand and possibly quantify the hazard and risk associated with induced seismicity associated with energy technologies. These primarily relate to the strength of the ground shaking and whether it can be felt and if it might represent nuisance to people or a risk to structures. This suggests that microseismicity, with magnitudes of less than 2, does not pose a risk. Earthquakes that result in weak or moderate shaking are unlikely to result in damage to structures but may represent a nuisance if they occur frequently.
Figure 4.1. Questions to be addressed to understand and possibly quantify the hazard and risk associated with induced seismicity associated with energy technologies (from “Induced Seismicity Potential in Energy Technologies”, National Academy of Sciences, 2012)
5 Lessons and Experiences from Seismic Monitoring and Mitigation

5.1 OVERVIEW

A dense network of monitoring stations is essential for reliable detection and discrimination of induced seismic events, and to allay public concern. Models of the detection capability of past and present networks of sensors for detecting earthquakes confirm that existing earthquake catalogues are likely to be incomplete at magnitudes of less than 2.0 ML. A comparison of modelled ground motions for a range of earthquake magnitudes with existing regulatory limits for ground vibrations for quarrying and blasting suggests that earthquakes with magnitudes of 3.0 or less are unlikely to exceed the limits above cosmetic damage may occur except at distances of less than a few kilometres. Smaller earthquakes may also exceed acceptable levels, but again only at small distances of less than a few kilometres.

5.2 RELIABLE DETERMINATION OF EARTHQUAKE LOCATIONS

The proximity of the epicentre of the magnitude 2.3 Blackpool earthquake in 2011 to the site of ongoing hydraulic fracturing operations led to immediate speculation that the earthquake was linked to this. However, the closest seismometer to the site was approximately 75 km away, and although the calculated epicentre was less than 2 km northwest of the drill site, uncertainties in the location, particularly the depth, were large, making it difficult to conclusively link the earthquake with operations at the Preese Hall drill site. Figure 5.1 shows the earthquake location calculated using the NonLinLoc non-linear earthquake location algorithm (Lomax et al., 2009) with 36 phase arrivals from 25 stations. The scatter in the location probability distribution function (red dots), extends approximately 4 km in the horizontal plane and 5 km in the vertical plane.

![Figure 5.1](image)

Figure 5.1. Location calculated using NonLinLoc (Lomax et al., 2009) for the earthquake on 1st April 2011. The location was calculated using 36 phase arrivals from 25 stations. The blue stars show the maximum likelihood location. Red dots show the density-scatter in the
location probability distribution function. The Preese Hall site is at \((x, y) = (0, 0)\).


In May 2011, the British Geological Survey installed two seismometers close to the Preese Hall site. A further earthquake with a magnitude of 1.5 ML occurred on 27 May 2011, and again this was felt locally. Data from the nearby stations helped to reduce the uncertainty in location estimates (Figure 5.2) providing more conclusive evidence that the earthquakes were linked to the hydraulic fracturing. In addition, a number of other smaller earthquakes were also detected on 26 and 27 May while hydraulic fracturing was ongoing.

Figure 5.2. Location calculated using NonLinLoc (Lomax et al., 2009) for the earthquake on 27th May 2011. The location was calculated using 18 phase arrivals from 12 stations. The blue star shows the maximum likelihood location. Red dots show the density-scatter in the location probability distribution function. Open triangles show the locations of the two seismometers installed close to the Preese Hall. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016.

Figure 3.3 also clearly shows the improvement in detection capability following the installation of additional stations close to the Preese Hall site, with the detection of a number of earthquakes with lower magnitudes that could only be observed on these stations.

This example highlights the importance of an appropriate monitoring network for reliable detection and location of any seismic events before, during and after any operations that may induce seismic activity. It also shows how local monitoring stations are essential to reduce uncertainty and contribute to a robust scientific dataset that may be used to develop strategies that mitigate the incidence of induced seismicity.

5.3 DETERMINATION OF BACKGROUND ACTIVITY RATES

Given a region of homogeneous seismicity, the value of the rate parameter in any sub-region will scale with relative size of the region. For example, if a region where seismicity is homogeneous and has 1000 earthquakes above a given magnitude each year, a sub-region, whose area is ten
times smaller, will have 100 earthquakes above the same magnitude each year. Applying the seismicity rate for Scotland, which suggests there should be eight earthquakes with a magnitude of 2 or above each year, to an area the size of the Midland Valley, there will only be one earthquake with magnitude 2 or above each year. Scaling this to an even smaller area of 100 km$^2$ then there will be a magnitude 2 earthquake every 150 years. This has important implications for baseline monitoring in small regions, particularly where activity rates are low, since the number of earthquakes above the detection threshold of the network in that region in a given period of time may be very low. Either a longer period of observation or a reduction in the detection threshold will be required to reliably determine seismicity rates.

5.4 DETECTION CAPABILITY

The detection capability of any network of seismic sensors is a complex function of many factors including the distribution, density and characteristics of individual sensors, their local site and noise conditions, as well as processing software and processing strategies. The amplitude of the ground motions caused by any earthquake is a function of both the magnitude of the earthquake and the distance of the earthquake from the recording position. An event may be undetected because it is too small or too distant, so its signal is indistinguishable from the background noise on the sensors. Also, many detection algorithms require the signal from an event to exceed the background noise level by a certain ratio on a number of sensors for an event to be detected. If the density of the sensor network is low, this will only happen for larger events. The detection of small earthquakes thus requires relatively high sensor densities.

We use a simple model for the amplitude of seismic waves as a function of magnitude and distance, combined with a given sensor density and estimates of seismic noise at each sensor location, to calculate the theoretical detection capability of the BGS seismic monitoring network at different points in time. Figure 5.3 shows the variation in the magnitude of earthquakes that would be detected by the network in Central Scotland in: (a) 1970; (b) 1980; (c) 1990; and (d) 2016. A signal in excess of three times the noise level needs to be recorded on at least three sensors for an earthquake to be detected. We assume uniform noise levels at each station based on a UK average model.

There are clear differences in detection capability with time as a result of changing numbers and densities of sensors. In 1970, the network was centred on Edinburgh, then expanded over the next two decades. Detection capability is observed to increase with time from 1970 to 1990 across the area of the scoping study in the Midland Valley as more sensors were installed. Post-1990 the network becomes more uniform but with a wider sensor spacing, which results in some local reduction in detection capability, e.g. around Glasgow. It is important to note that at no time was the network able to reliably detect earthquakes with a magnitude of 0.5 or below, even in areas of relatively high station densities.

Reliable location and magnitude measurement places additional constraint on network design, since measurements at more stations are needed than for detection alone. In addition, location errors depend on the distribution and density of the recording stations. These errors may be large if the station density is insufficient, or if the closest stations are far from the earthquake source. As we show above, large errors can limit the ability to discriminate between induced and natural earthquakes.

In general, the results support our use of a magnitude of completeness of 2.0 for the Scottish earthquake catalogue and for calculation of activity rates and recurrence parameters. However, completeness will also vary as a result of failure of instrumentation and variations on background noise levels at individual sites.
Figure 5.3. Modelled detection capability for the BGS seismic monitoring network (black triangles) in central Scotland at four points in time: (a) 1970; (b) 1980; (c) 1990; and (d) 2016. The contours show the spatial variation in magnitudes that can be detected. Detection requires a signal in excess of three times the background noise to be recorded at three or more stations. The scoping study area is delineated by the grey shaded area.

5.5 POSSIBLE GROUND MOTIONS FOR SMALL AND MODERATE EARTHQUAKES

Seismic hazard is often expressed as the probability of a particular level of ground motion being exceeded within a certain period of time. Accurate assessment of seismic hazard requires knowledge of how ground motion relates to the characteristics of an earthquake, how it attenuates with distance, and how it might be affected by the geological conditions at the site of interest. In the assessment of seismic hazard, strong ground motions are commonly estimated using empirical ground motion prediction equations (GMPEs). Abramhamson et al., (2008) provide a comparison of the recent Next Generation Attenuation (NGA) models. However, the choice of an appropriate model is often difficult, since in most parts of the world there are
insufficient data to produce well-constrained empirical models. In such cases it is now becoming generally accepted that it is more appropriate to use a robust ground motion model derived from a large international data set with the widest possible sampling of the magnitude-distance domain than a local model that may be less well constrained (Douglas, 2007; Bommer et al., 2007). For example, the SHARE\textsuperscript{13} project used a number of GMPEs including Chiou and Youngs (2008) and Akkar & Bommer (2010).

An alternative approach is to simulate ground motion using stochastic modelling based on the earthquake source parameters as well as parameters to characterise path and site effects (Boore, 1983, 2003). Here, we use this approach and the SMSIM software (Boore, 2005) to explore possible ground motions for small to moderate earthquakes that might occur in Ireland, and compare these with some existing regulations for vibrations from blasting in the UK.

The earthquake source is parameterised by the seismic moment, source spectrum shape and stress drop. The former can be calculated directly from earthquake magnitude (Hanks and Kanamori, 1979). Here, we assume that for small magnitudes local magnitude, $M_L$, is approximately equal to moment magnitude, $M_W$. We use a single corner frequency model for the shape of the source spectrum (Brune, 1970). Stress drop is an important parameter in the dynamics of the rupture process and can have a strong effect on recorded ground motions. However, most earthquakes have stress drops in the range of a few MPa to a few tens of MPa. Here, a fixed stress drop of 3 MPa has been assumed.

Path effects are incorporated using geometrical spreading and anelastic attenuation terms. At short hypocentral distances geometrical spreading is dominated by the body wave term and we use the path attenuation quality factor determined for the UK by Sargeant and Ottemoller (2008). We do not consider either site-specific attenuation or amplification. Note that hypocentral distance is the distance between the earthquakes focus and the observer that includes the effect of the earthquake focal depth. As a result, the greater the focal depth, the greater the hypocentral distance. Earthquakes induced by anthropogenic activities often occur at very shallow depth. For example, earthquakes related to coal mining in the UK often have depths of around 1 km, corresponding to the depth of the mining activity. Similarly, the earthquakes induced by hydraulic fracturing operations at Preese Hall, Blackpool, UK, occurred at depths of approximately 3 km, close to the point of fluid injection. This means that despite having generally small magnitudes, such induced earthquakes can often be felt as a result of their proximity to the surface.

Figure 5.4 shows curves (coloured lines) of ground velocity as a function of hypocentral distance calculated for earthquakes with magnitudes of 2.0, 3.0, 4.0 and 5.0. The dashed lines show the limits for acceptable levels of ground vibrations caused by blasting from BS 6472-2 and also the limits for vibrations caused by blasting, above which cosmetic damage could take place (BS 7385-2). Blasting occurs on a regular basis throughout the British Isles and maximum magnitudes for quarry blasts recorded in the BGS catalogue are around 2.5 $M_L$. The limits specified by BS 6472-2 are 6-10 mm/s during the working day, 2 mm/s at night time and 4.5 mm/s at other times. BS 7385-2 gives limits of 15 mm/s at 4 Hz, increasing to 20 mm/s at 15 Hz and 50 mm/s at 50 Hz. The limits increase with the frequency of the vibration since high frequency vibrations are less likely to cause damage. In simple terms, the observed frequencies for earthquake ground motions are largely controlled by the magnitude of the earthquakes and the stress drop, although anelastic attenuation and site conditions can also play an important role.

Earthquakes with magnitudes of 4.0 or above may approach the limits above which cosmetic damage may be observed, as specified in BS 7385-2, but generally only at hypocentral distances of less than 10 km. Smaller earthquakes, with magnitudes of 3.0 may also exceed the limits recommended in BS 6472-2, though at even smaller distances of less than a few kilometres. This seems reasonably consistent with observations that the largest mining-induced earthquakes, with
magnitudes of around 3.0 $M_L$, caused some superficial damage (Westbrook et al., 1980; Redmayne, 1998) including, minor cracks in plaster and harling.

Given the strong variability of observed ground motions from earthquakes, as well as the influence of factors such as variable stress drops and site conditions, which have not been included in our calculations, the modelled ground motion shown here should be considered as indicative only, rather than encompassing the fully extent of possible ground motions in this magnitude and distance range. However, we do find good general agreement, between our calculations and many observations of small earthquakes in the British Isles.

![Graph of modelled peak ground velocity](image)

**Figure 5.4:** Modelled peak ground velocity (solid coloured lines) plotted as a function of hypocentral distance. The grey dashed lines show the limits for acceptable vibrations from blasting specified in BS 6472-1 and BS 7385-2. The squares and triangles show observed horizontal and vertical ground motions.
6 Lessons from the Research

Hydraulic fracturing to recover hydrocarbons is generally accompanied by earthquakes with magnitudes of less than 2 ML that are too small to be felt. In the United States, the large number of hydraulic fracturing operations (1.8 million) and the small number of felt earthquakes directly linked to them (3) suggests that the probability of induced earthquakes that can be felt is small. In western Canada, there are more examples of induced earthquakes with magnitudes larger than 3 than in the United States. These include a magnitude 4.4 earthquake, which is the largest earthquake linked to hydraulic fracturing in the world. However, given the large number of hydraulically fractured wells (>12,000), the probability of induced earthquakes that are large enough to be felt also appears to be small.

Well-documented increases in earthquake rates and significant earthquakes in many areas of the Central and Eastern United States have been linked to wastewater injection in deep disposal wells rather than hydraulic fracturing, and seismic hazard forecasts for these areas now include contributions from both induced and natural earthquakes. These forecasts show increases in earthquake hazard by a factor of 3 or more in some areas of induced earthquake activity. However, it is important to note that most wastewater injection wells are not associated with any earthquake activity. Additionally, the nature of the wastewater injected into deep wells varies: while some comes from hydraulic fracturing used in unconventional oil and gas production, many wastewater injection wells are used to dispose of produced water from conventional hydrocarbon production.

Studies of earthquake activity in the Raton Basin an area that has produced coal-bed methane since 1994, provides strong evidence that a this activity is related to the subsequent disposal of wastewater from the coal-bed methane extraction process by injection into deep wells, rather than from the extraction process itself. Literature was not located concerning induced seismicity and coal-bed methane extraction in Canada, Australia or other parts of the USA, suggesting that this is not a major issue in those areas.

A detailed examination of existing earthquake catalogues has shown that seismic activity in Scotland is low. Historical records of earthquakes in Scotland date back to the 16th century, and show that despite many accounts of earthquakes felt by people, damaging earthquakes are relatively rare. The largest recorded earthquake in Scotland had a magnitude of 5.2 ML and only two other earthquakes with magnitudes of 5.0 ML or greater have been observed in the last 400 years. As a result, the risk of damaging earthquakes is low.

Most earthquake activity in Scotland lies north of the Highland Boundary Fault. Earthquake activity in the Midland Valley of Scotland is lower and most of the recorded earthquakes in this area in the 1970’s, 1980’s and 1990’s were induced by coal-mining. Since the decline of the coal-mining industry in the 1990’s, very few mining-induced earthquakes have been recorded. Most of the mining induced earthquakes are small and the largest mining-induced earthquakes in Scotland had a magnitude of 2.6 ML. Earthquake activity rates calculated for the Midland Valley are lower than north of the Highland Boundary Fault, suggesting that earthquake risk is even lower here than elsewhere in Scotland. However, the small number of observed earthquakes for this area means the values have large uncertainties.

Existing catalogues of earthquake activity in Scotland are incomplete at magnitudes below 2 ML, from 1970 to present, and for higher magnitudes prior to this. This is due to the detection capability of the networks of seismometers that have operated in the study area over the last few decades. This, together with the low background activity rates limits our ability to identify any areas that might present an elevated seismic hazard for any Unconventional Oil and Gas operations based on seismic data alone. Better earthquake catalogues will be needed to rectify
this and provide reliable estimates of background activity rates and that allow the discrimination and forecasting of induced seismic activity. This will require denser arrays of seismic instrumentation that currently deployed. These dense arrays are also required to provide high-quality, real-time earthquake locations, which are required as part of any traffic light system for mitigating risk.

Earthquake focal mechanisms provide both fault geometries and principal stress directions that can be used to constrain our understanding of the driving forces of current deformation. The observed orientation of the maximum and minimum compressive stresses means that the reactivation potential of faults that strike either NE-SW or NW-SE are interpreted, based on existing data, to be highest, with the former optimally oriented for left-lateral strike-slip motion. This means that fault systems that follow the widely observed Caledonian trend may have a higher reactivation potential than other orientations. However, the reactivation potential for E-W or ENE-WSW striking faults in the Midland Valley region is interpreted to be low based on current data. This seems in keeping with the low levels of observed seismicity in this part of Scotland. However, the limited number of focal mechanisms for earthquakes in Scotland, along with other reliable stress indicators such as borehole breakouts means that it is not possible to identify any particular parts of the study area where the fault reactivation potential is higher or that may present an elevated seismic hazard for any UOG operations.

In addition, our knowledge of fault systems in the sub-surface is generally limited to areas where detailed geophysical surveys have been carried out. For example in the case of the Blackpool earthquake activity, the existing geophysical data was insufficient to identify any faulting close to the Preese Hall well prior to hydraulic fracturing operations, although Clarke et al. (2014) subsequently identified a possible causative fault close to the well using data from a later detailed 3-D seismic reflection study. Improved understanding of the hazard from induced earthquakes and the successful implementation of regulatory measures to mitigate the risk of induced seismicity are likely to require new geological and geophysical data that can be used to map sub-surface fault systems in high resolution as well as more measurements of the orientation of magnitude of the sub-surface stress field.

Regulatory measures for the mitigation of induced seismicity (DECC, 2013) include: avoiding faults during hydraulic fracturing; assessing baseline earthquake activity; monitoring seismic activity during and after fracturing; and a ‘traffic light’ system that controls whether injection can proceed or not, based on that seismic activity. These are similar to regulatory measures that are in place in the US and Canada. In the US, much of this regulation is aimed at induced seismicity related to wastewater disposal in deep wells, although this is also relevant to induced seismicity from hydraulic fracturing.

In the UK, the magnitude limit for the cessation of hydraulic fracturing operations (0.5 ML) is considerably less than the limits in California (2.7 ML) and Illinois, Alberta and British Columbia (4.0 ML), and may be considered a conservative threshold. Local monitoring systems that are capable of reliable measurement of earthquakes with very small magnitudes will be required to implement the UK limit successfully. A magnitude 4.0 ML earthquake in an area of high population density, such as the Midland Valley of Scotland, would be strongly felt by many people and may even cause some superficial damage.

British Standards BS 6472-2 and BS 7385-2 define limits for acceptable levels of ground vibrations caused by blasting and quarrying and the limits for vibrations caused by blasting, above which cosmetic damage could take place. A comparison of modelled ground motions for a range of earthquake magnitudes with these limits suggests that earthquakes with magnitudes of 3.0 or less are unlikely to exceed the limits above which cosmetic damage may occur, as set out in BS 7385-2, except at distances of less than a few kilometres. This seems reasonably consistent with observations that the largest mining-induced earthquakes, with magnitudes of around 3.0 ML, caused some superficial damage (Westbrook et al., 1980; Redmayne, 1998) including, minor cracks in plaster and harling. Smaller earthquakes may also exceed the limits for vibration
set out in BS 6472-2, but again only at small distances of less than a few kilometres. An alternative traffic light system could use these vibration limits as well as, the current magnitude thresholds.

Improved understanding of the hazard from induced earthquakes and the successful implementation of regulatory measures to mitigate the risk of induced seismicity is likely to require industrial data from hydraulic fracturing operations such as injection rates and volumes, along with downhole pressures, in addition to seismic, geological and geophysical data.
Glossary

**Activity Rate**: a function of the total number of earthquakes in a given region of space and time that expresses how seismically active that region is.

**Anthropogenic**: relating to, or resulting from the influence of human beings.

**Borehole Breakouts**: enlargements or elongations in the cross-section of a wellbore in a direction parallel to the minimum (least) horizontal stress.

**Earthquake**: shaking of the ground surface caused by the sudden movement along faults within the Earth which releases energy in the form of seismic waves that propagate through the Earth. Such movement on the faults is generally a response to long term deformation and build-up of stress, caused by processes such as plate tectonics.

**Earthquake Magnitude**: a measure of the amount of energy released during an earthquake. This depends on both the area of the fault that ruptures and also the amount of slip or displacement on the rupture plane.

**Earthquake Triggering**: the promotion of the occurrence of future earthquakes due to stress perturbations in the Earth’s crust.

**Enhanced Geothermal System**: a geothermal system uses heat from deep in the ground to generate energy. An enhanced geothermal system is one where the natural connectivity does not permit sufficient flow and additional stimulation is required.

**Fault**: a fracture in the Earth’s crust across which the rocks have been displaced relative to each other.

**Fold**: a bend in planar structures such as rock strata or bedding planes.

**Hydraulic Fracturing (“Fracking”)**: a process used to increase the permeability of a rock through the creation of networks of interconnected fractures by the injection of pressurised fluids.

**Induced Seismicity**: seismic activity resulting from changes in the state of stress in the Earth caused by anthropogenic (human) activities. Activities such as underground mining, deep artificial water reservoirs, oil and gas extraction, geothermal power generation and waste disposal can all result in induced seismicity.

**Joints**: a fracture, or potential fracture, in a rock adjacent to which there has been no displacement.

**Lithology**: the character of a rock expressed in terms of its mineral composition, structure, grain size and arrangement of its constituents.

**Microseismicity**: earthquakes with magnitudes of less than 2.0 and too small to be felt.

**Permeability**: a measure of the ability of a rock to allow fluids to pass through it.

**Sedimentary Rock**: a rock formed in one of three main ways: by the deposition of the weathered remains of other rocks; by the deposition of the results of biogenic activity; and by precipitation from solution.

**Seismic Hazard**: a property of an earthquake that can cause damage and loss, like ground shaking. Often expressed as a probability that a given level of ground shaking level being exceeded within a period of time.

**Shale**: a fine grained sedimentary rock.

**Shale Gas**: a natural gas found in shale (can also be referred to as unconventional gas).
**Stratigraphy:** the definition and description of the stratified rocks of the Earth’s crust.

**Stress:** force applied over a given area and resulting in the deformation of the rock mass.

**Traffic Light System:** a system for mitigating earthquake risk that uses real-time monitoring of seismic activity. Operations continue (green), proceed with caution (amber) or stop (red) depending on the observed level of seismic activity.

**Waste Water Disposal:** the disposal of waste water from the hydrocarbon and other industries into deep wells. This process often involves large volume of fluid that is injected over long periods of time.

**Well Integrity:** the ability of the well to prevent hydrocarbons or operational fluids leaking into the surrounding environment.
Data and Resources

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Faults other geological data for the UK are from the British Geological Survey DigMapGB series, ©NERC 2016. Available at http://www.bgs.ac.uk/products/digitalmaps/digmapgb.html

Earthquake data for the UK is from the British Geological Survey UK Earthquake Catalogue © NERC 2016. Licensed under OGL (Open Government Licence) and available at http://earthquakes.bgs.ac.uk

Coal Mining Reporting Area data is published by the Coal Authority and licensed under OGL (Open Government Licence) and available at https://data.gov.uk/dataset/coal-mining-reporting-area

Earthquake data for the US is from the ANSS Comprehensive Earthquake Catalog (ComCat), credit: U.S. Geological Survey. Available at http://earthquake.usgs.gov/earthquakes/search/


Figure 3.11 showing areas impacted by induced earthquakes as well as the location of fluid injection wells, is published by the U.S. Geological Survey at https://earthquake.usgs.gov/hazards/induced. Credit: U.S. Geological Survey, Department of the Interior, U.S.G.S. Open-File Report OFR-2016-1035

Figure 3.12 showing the intensity of potential ground shaking with a 1% probability of being exceeded in one year, is published by the U.S. Geological Survey at https://earthquake.usgs.gov/hazards/induced. Credit: U.S. Geological Survey, Department of the Interior, U.S.G.S. Open-File Report OFR-2016-1035


Smoothed maximum horizontal compressive stress, sH, direction obtained from the World Stress Map Release 2008 (Heidbach et al., 2010). Available at http://dc-app3-14.gfz-potsdam.de/pub/download_data/download_data.html
References

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


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