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Unconventional Gas Exploration and Extraction (UGEE) Joint Research Programme

Summary Report 2: Baseline Characterisation of Seismicity

Authors: Brian Baptie, Colm Jordan, Ilaria Mosca, Francesca Cigna, Sean Burke, John McCloskey, Mairéad Nic Bhloscaidh, Chris Bean and Martin Möllhoff

Broadband seismometer deployed in a field pit

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On the 23rd of July 2016, the Department of Communications, Energy and Natural Resources (DCENR) became the DCCAE. Along with a name change, the new Department incorporates functions that were formerly held within the Environment Division of the DECLG. The Department retains responsibility for the Telecommunications, Broadcasting and Energy sectors. It regulates, protects, develops and advises on the Natural Resources of Ireland. Of particular relevance is the role of the Petroleum Affairs Division (PAD) to maximise the benefits to the State from exploration for and production of indigenous oil and gas resources, while ensuring that activities are conducted safely and with due regard to their impact on the environment and other land/sea users. The Geological Survey of Ireland (GSI) is also within DCCAE and provides advice and guidance in all areas of geology including geohazards and groundwater and maintains strong connections to geoscience expertise in Ireland.

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Administration of the Research Programme and Steering Committee

This Research Programme is being administered by the EPA and steered by a committee with representatives from DCCAE (formerly DCENR and the Environment Division of the DECLG), the Commission for Energy Regulation (CER), An Bord Pleanála (ABP), the GSI, NIEA, the Geological Survey of Northern Ireland (GSNI), as well as a Health representative nominated by the Health Service Executive (HSE).

UGEE Joint Research Programme

Environmental Impacts of Unconventional Gas Exploration and Extraction (UGEE)

(2014-W-UGEE-1)

Summary Report 2:

Baseline Characterisation of Seismicity

by

British Geological Survey, University College Dublin, Ulster University, CDM Smith Ireland

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References to government departments (DCENR and DCELG) throughout the report use the names of these departments prior to July 2016. References to the Department for the Economy (DfE) throughout the report use the name of its predecessor, the Department of Enterprise Trade and Investment (DETI), the department responsible for petroleum licensing in Northern Ireland until May 2016.

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Project A2 Internal Review Panel[1]

University College Dublin, British Geological Survey, University of Ulster

1 More details available at: http://www.epa.ie/pubs/reports/research/ugeejointresearchprogramme/ugeejrptasksorganisations.html

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Executive Summary

Unconventional gas exploration and extraction (UGEE) involves hydraulic fracturing (fracking) of low-permeability rock to permit the extraction of natural gas on a commercial scale from unconventional sources, such as shale gas deposits, coal seams and tight sandstone. The Environmental Protection Agency (EPA), the Department of Communications, Energy and Natural Resources (DCENR) and the Northern Ireland Environment Agency (NIEA) awarded a contract in August 2014 to a consortium led by CDM Smith Ireland Limited to carry out a 24-month research programme looking at the potential impacts on the environment and human health from UGEE projects and operations (including construction, operation and after-care).

The Joint Research Programme (JRP) on the Environmental Impacts of Unconventional Gas Exploration and Extraction[2] is composed of five inter-linked projects designed to produce a scientific basis that will assist regulators – in both Ireland and Northern Ireland – in making an informed decision about whether or not it is environmentally safe to allow fracking. As well as undertaking research in the island of Ireland, the UGEE JRP examined and collated evidence from other countries.

The JRP has examined the process, impacts and mitigation measures associated with hydraulic fracturing around the world. International regulatory frameworks have been reviewed, along with the suitability of legislation in Ireland and Northern Ireland, and potential gaps identified.

Project A2 of the UGEE JRP, which is the subject of this summary report, addressed seismic activity in relation to hydraulic fracturing and the design of a baseline seismic monitoring network for the two study areas of the Northwest Carboniferous Basin (NCB) and the Clare Basin (CB).

The process of hydraulic fracturing is generally accompanied by microseismicity, usually defined as earthquakes with magnitudes of two or less that are too small to be felt by most people. Two types of induced events can be defined: "fracked" events, whose size is constrained by the energy of the injection process, and "triggered" events, whose size depends largely on the amount of stored-up elastic strain energy already present in the rocks. Seismicity associated with international UGEE projects and operations were reviewed and the potential for induced earthquakes in the study areas assessed.

Baseline monitoring is frequently cited as a pre-condition for licensing of unconventional gas exploration and extraction (UGEE) activity. Therefore, the Terms of Reference and scope of work for the Joint Research Project (JRP) on the environmental impacts of UGEE identified a requirement to identify, evaluate and undertake appropriate potential baseline monitoring requirements for water, air and seismicity (earthquake activity). Requirements for baseline monitoring are embodied in the (2014/70/EU) EC Recommendation on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing, but a review of international literature provides relatively little on the specifics of baseline monitoring.

Following a comprehensive assessment of the two study areas and the existing provisions for monitoring, the JRP made proposals for baseline monitoring for the assessment of water and naturally occurring seismicity, with a window of up to 2 years proposed to complete the aforementioned baseline monitoring programme. Consequently, such a baseline monitoring programme would result in the overall findings of the research being delivered after the project deadline of 2016.

The original timeline for the research envisaged that the entire programme, including water and seismicity baseline data acquisition, would conclude by 2016. The steering committee considered that, were the baseline acquisition to commence, the revised timeline for the overall research programme would now be to report in 2018 at the earliest. The decision was therefore taken to prepare an integrated synthesis report now, drawing together the conclusions of the research to date in order that these findings could be reviewed and policy decisions formulated with regard to the use of this technology in Ireland.

2 www.ugeeresearch.ie

It is noted that the baseline monitoring programme proposed by the JRP remains valid and the report includes a recommendation that such a programme should be implemented in advance of the consideration of any application for a Petroleum Exploration Licence (Ireland) or an application to carry out high-volume hydraulic fracturing (Northern Ireland). It should be noted that such a baseline monitoring programme should provide independent information and is therefore different from any baseline characterisation and monitoring that would be required of UGEE operators as part of a licensing process, which would be project and site specific, and would be designed to monitor specific receptors.

Natural seismic activity in Ireland is very low and is much lower than that of the neighbouring countries of Wales, England and Scotland. Current theory suggests that "triggered" earthquake activity is likely to be the result of amplification of the existing seismicity; the very low background activity in Ireland means that it is extremely unlikely that hydraulic fracturing will have any potentially troublesome seismic consequences. However, background seismicity is known to be spatially very variable and the lack of monitoring in the two study areas means that the background levels remain unknown. Consequently, detailed baseline monitoring should be an essential requirement for any future unconventional gas exploration and extraction. Because of the low natural seismicity, a relatively long period of baseline monitoring may be required to reliably determine the natural rates in each area.

The geothermal industry has implemented extensive seismic monitoring and this may be considered as best practice for UGEE for the monitoring of earthquake activity, along with appropriate control measures for the mitigation of risks associated with induced earthquakes.

The study 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, to reduce uncertainty and also to allay public concern.

Authoritative ground surface monitoring is vital in relation to UGEE projects to accurately understand the degree of any surface motion during operations. Quantitative measurements of ground motion, both historical and current, are required to confirm any surface displacement and enable the assessment of the impacts on the surface environment and the structures built upon or within it. Investment in ground surface-monitoring equipment is essential to gauge potential damage and to address the potential concerns of the public and policymakers regarding impacts on the environment. The availability of data and new analysis methods, such as the interferometric synthetic aperture radar (InSAR) technique, are available for the island of Ireland. In combination with the InSAR technique, complementary *in situ* methods such as the Global Navigation Satellite System and tiltmeters could be deployed, since integrating different monitoring techniques provides better and more detailed information on deformation.

It is well known that the island of Ireland is a region of low seismic activity. Historical earthquakes in Ireland had low intensities and were generally felt only over small areas, suggesting that they were small in magnitude. Instrumental data from the Dublin Institute of Advanced Studies (DIAS) and the British Geological Survey (BGS) catalogues also confirm the low rates of seismic activity reported historically. Nearly all of the seismic activity in the island of Ireland has been concentrated around the coast.

Modelling of possible ground motions for realistic examples of small to moderate earthquakes that might occur in Ireland suggests that ground velocities are unlikely to exceed typical levels at which cosmetic damage might occur, except close to the earthquake source.

Advanced modelling approaches were developed to forecast the triggered seismicity surrounding a hydraulic fracturing operation for a series of scenarios with different reference activity levels and baseline network qualities.

Existing fault structures have a significant effect on the success of the seismicity forecasts and systematic errors can be introduced into induced rate estimates by assuming homogeneous reference rates (which is necessary in the absence of adequate information describing the structural geology). In addition, current data catalogues for the study areas are completely inadequate for forecast modelling on the study areas' spatial scales and to the standard necessary. The necessary use of synthetic data catalogues in this work to represent hypothetical baseline scenarios allowed illustration of the nature of the uncertainties that might be expected.

Robust forecasts of the hazard-relevant parameters of induced earthquake catalogues can be made only using a high-quality baseline network and local sensor networks deployed during operations together with current best practice in data analysis. The data are necessary to establish the rate of naturally occurring seismicity in an area that can then be compared with the seismicity recorded during any hydraulic fracturing operations; it is also useful to locate active faults and to map seismic noise levels in detail.

Existing seismic networks in the island of Ireland are not sufficient to detect and locate all local earthquakes with a local magnitude ≥0.5 ML in the two study areas. Local example networks for the two study areas with interstation spacings between 15 and 25 km were designed; these could reliably locate all such events during a baseline study, which should operate for at least 2 years. This would require the deployment of at least 12 seismometers in the NCB and 10 seismometers in the CB.

The baseline network would be implemented and operated most effectively by a commercial entity, but it was recommended that the data should be integrated with data held at the National Data Centre (NDC) and operated as part of the Irish National Seismic Network. The resulting earthquake catalogue, together with the seismic raw data, should be made publicly available through the NDC to ensure transparency.

The general consensus in the literature is that the process of hydraulic fracturing, as presently implemented for shale gas recovery, does not pose a high risk for inducing either felt, damaging or destructive earthquakes. Worldwide, there are only five documented examples of earthquakes with magnitudes greater than two that have been conclusively linked to hydraulic fracturing.

In contrast, evidence of changes in observed seismicity linked to long-term disposal of wastewater by deep well injection from the hydrocarbon and other industries suggests that this activity may pose a greater seismic risk than UGEE operations. For example, the observed increases in earthquake rates and the number of significant earthquakes in many areas of the central and eastern USA, which have been linked to wastewater injection in deep disposal wells, provides a considerable body of evidence that it makes a non-negligible contribution to seismic hazard.

The enhanced geothermal systems industry has developed a series of measures to address induced seismicity that may be considered as industry best practice and, as such, may be considered appropriate for mitigating the risk of induced seismicity in UGEE operations.

There remain gaps in existing knowledge of induced seismicity. For example, the pre-existing state of stress and pore pressure acting on a fault are usually unknown. Triggered events can be initiated by very small stress perturbations; however, the potential for such events depends very much on the geological context and, given the low levels of background seismicity, the probability of large triggered seismic events in Ireland can be considered to be small.

During any hydraulic fracturing operations, site-specific seismic monitoring and detailed recording of injection parameters is necessary, to reduce uncertainties in earthquake locations and to compare the temporal evolution of seismic activity with operational activities.

A stochastic model that used the distribution of event sizes from other wells was developed, allowing modelling of the formation of fractures from widely accepted empirical scaling relations. The parameters used for the model are for illustration; they should be replaced by values determined initially from a baseline survey and subsequently updated in near real-time during any fracking operation.

There is clear evidence that vertical fractures can propagate into shallow depths; if the fracking is sufficiently shallow, there is a risk that these fractures might interact with aquifers. Data show an upward extent of microseismicity of approximately 100 m, with a worst-case event extending up to 300 m above the perforation. Fracture lengths show a strong decrease in probability with length. However, there is a relatively long tail on the statistical distribution, which can never reach a probability of zero, suggesting that there could be very rare large events.

Combining the distance of the microseismic event from the perforation and the length of fracture associated with the bigger events, it was estimated that approximately 95% of projects would have fractures less than 300 m above the perforation, but that there is a finite probability of fractures exceeding 500 m.

During fracking, the permeability of the entire rock volume is increased by a set of fractures connecting any permeable (pre-existing) through-going faults to the fracked volume, thereby potentially connecting the fracked volume to the surface. This process has not been addressed in this study, because there is insufficient information about the distribution and vertical extent of such permeable pathways.

The baseline monitoring of seismicity and the analysis of the measured data had not been carried out at the time of publication of this report. This has limited the efficacy of the models developed to predict seismicity and fracture lengths generated by UGEE operations and to assess the risk of migration of pollutants along these fractures to sub-surface aquifers in the study areas.

This project assessed the potential risk of seismic activity induced by UGEE operations and examined international experience of such induced activity, natural seismic activity in the island of Ireland, and methodologies for monitoring distortion of the surface and of background and induced seismic activity, and it developed techniques for predicting induced seismicity.

There is a general consensus that UGEE operations can result in low-magnitude seismic activity from the hydraulic fracturing process, but that these events are unlikely to cause damage or even be felt. Larger events could occur if slippage on existing faults is initiated, but this is considered to be highly unlikely in the island of Ireland, where the available data indicate that the rate of natural seismicity is extremely low. A greater risk is perceived as a result of the injection of high volumes of wastewater that might result from UGEE operations; therefore any such proposals should be examined in detail in the context of the local site geology.

Modelling techniques developed by this project offer the potential to predict earthquake activity, including fracture lengths. Improved understanding of the hazard from induced earthquakes requires better baseline data on the geological structure of the study areas, background seismicity to provide input parameters for the models and industrial data from hydraulic fracturing operations such as injection rates, volumes and downhole pressures. Using conservative assumptions, the modelling demonstrated that fracture lengths from hydraulic fracturing are relatively short and extremely unlikely to exceed 500 m; as a consequence, pollution of aquifers would not occur by movement of pollutants along fracture paths as long as the separation between the fracture zone and the aquifer exceeds this distance.

Detailed seismic monitoring would be required during any UGEE operations and should be linked to a traffic light system to control operations should seismic activity occur.

1 Introduction

1.1 Overall Project

Unconventional gas exploration and extraction (UGEE) involves hydraulic fracturing (fracking) of low-permeability rock to permit the extraction of natural gas on a commercial scale from unconventional sources such as shale gas deposits, coal seams and tight sandstone. The Environmental Protection Agency (EPA), the Department of Communications, Energy and Natural Resources (DCENR) and the Northern Ireland Environment Agency (NIEA) awarded a contract in August 2014 to a consortium led by CDM Smith Ireland Limited to carry out a 24-month research programme looking at the potential impacts on the environment and human health from UGEE projects and operations (including construction, operation and after-care).

The UGEE Joint Research Programme (JRP)[3] was composed of five interlinked projects and involved field studies (baseline monitoring of water and seismicity), as well as an extensive desk-based literature review of UGEE practices and regulations worldwide.

- Project A1 (Groundwater, Surface Water and Associated Ecosystems) dealt with the baseline characterisation of groundwater, surface water and associated ecosystems, which is required for potential impacts to be assessed.
- Project A2 (Seismicity) dealt with the baseline characterisation of seismicity, which is required for potential impacts to be assessed.
- Project A3 (Air Quality) dealt with the requirements and needs for additional air baseline monitoring (frequency, location and types of pollutants to be covered) in the context of Environmental Impact Statements (EISs).
- Project B (UGEE Projects/Operations: Impacts and Mitigation Measures) covered the identification and detailed examination of the potential impacts on the environment and human health, as well as successful mitigation measures to counteract these impacts, associated with UGEE projects/operations that have come to the fore worldwide, using published reports and other sources.
- Project C (Regulatory Framework for Environmental Protection) was aimed at identifying all regulatory requirements, including gaps in existing regulations and best operational practices associated with the establishment and operation of UGEE projects/operations in the context of the island of Ireland.

The UGEE JRP was designed to produce the scientific basis that will assist regulators – in both Ireland and Northern Ireland – in making an informed decision about whether or not it is environmentally safe to allow fracking. As well as examining research in the island of Ireland, the UGEE JRP is looking at and collating evidence from other countries.

1.2 Objectives and Aims of Project A2

Baseline characterisation of seismicity is required for potential impacts to be assessed. The research covered by Project A2 (Seismicity) includes:

- a review of records of natural seismicity in the island of Ireland;
- an assessment of the nature and magnitude of induced seismicity and other activities associated with hydraulic fracturing operations worldwide;
- a review of seismic risk control regimes operated worldwide for UGEE projects/operations and recommendations for systems applicable to the island of Ireland, with particular reference to the case study areas;
- an assessment of the capability of existing seismic monitoring network(s) to allow detection and location of seismic events down to low thresholds, and recommendations for future development of the seismic monitoring network;
- an assessment of microseismic monitoring methodologies enabling real-time assessment of seismicity associated with hydraulic fracturing;
- linking with Project B – an assessment of the success of pre-fracturing modelling techniques to predict the propagation of fractures and the risk of fractures creating preferential pathways for pollutants.

3 http://www.ugeeresearch.ie

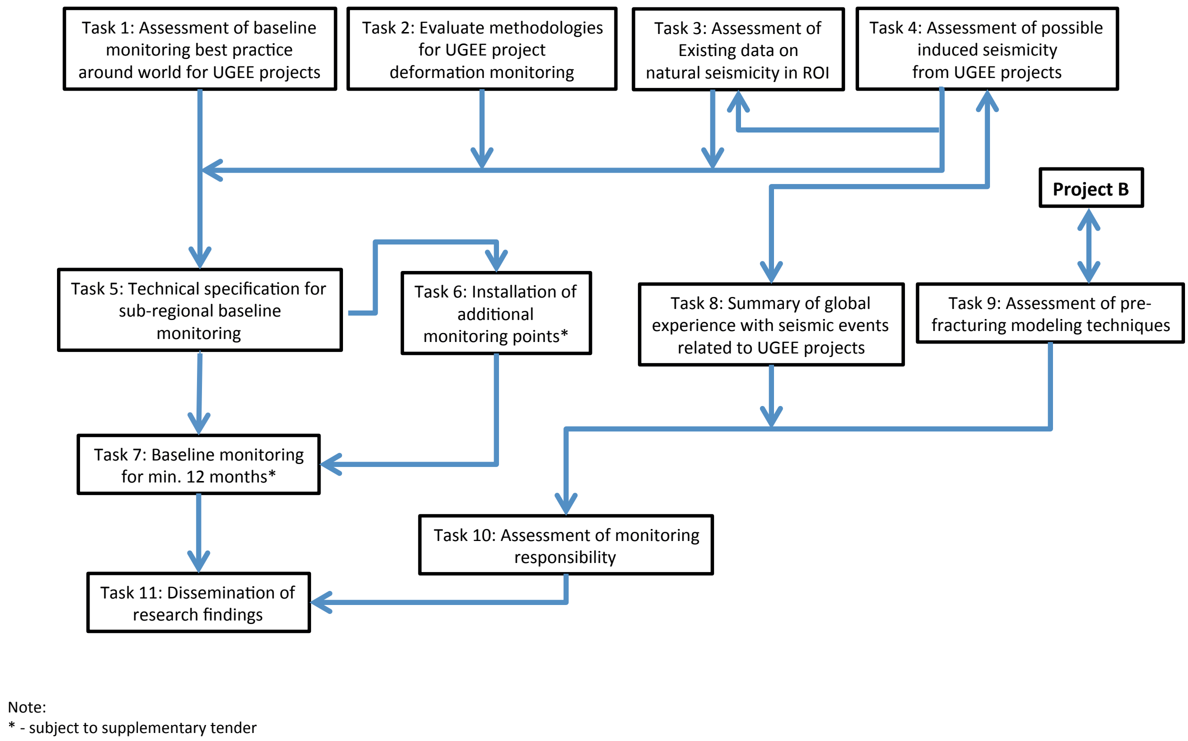

Figure 1.1. Project A2 tasks and goals.

This report summarises the outputs of Tasks 1, 2, 3, 4, 8 and 9 as presented in *Final Report 2: Baseline Characterisation of Seismicity*. The structure of Project A2 is shown in Figure 1.1; Tasks 6 and 7 (installation of a baseline monitoring network and its operation and data analysis) were not progressed by the steering committee.

1.3 Methodology and Information Sources

1.3.1 Task 1: Assessment of existing baseline monitoring operated worldwide for UGEE projects/operations

This task examined some of the fundamental principles of earthquakes and seismology that are important for seismic monitoring. These included frequency–magnitude distributions for earthquakes and how activity rates are likely to affect required durations of monitoring both before commencement and after cessation of any UGEE operations. It also considered requirements for the reliable detection and location of earthquakes, particularly regarding how station density needs to increase to detect and locate smaller earthquakes in any given region. Finally, some examples of how baseline monitoring has been used in the geothermal industry were described, as well as examples of how microseismic monitoring can be used to monitor a fractured volume.

1.3.2 Task 2: Evaluate methodologies for the monitoring of ground deformation that may be associated with UGEE projects/operations

This task outlined radar data availability and presented the results of a study of the feasibility of applying interferometric synthetic aperture radar (InSAR) to monitor ground deformation across the island of Ireland using elevation and land cover data. As well as the regional coverage afforded by InSAR, the technique also benefits from an archive of data (from 1992), which can be used to gain a baseline of surface motion over a site where tiltmeters or the Global Navigation Satellite System (GNSS) were not already installed prior to operations. Since InSAR monitoring is generally applied to urban areas (due to the presence of abundant reflectors), this task also examined the application of this technique to monitoring potential ground deformation in non-urban areas of Ireland.

1.3.3 Task 3: Assessment of existing data on natural seismicity in the island of Ireland

This task provided an updated review of earthquakes in Ireland. Historical data from available sources were combined with modern instrumental data to construct a single coherent catalogue with a uniform moment magnitude scale. This catalogue was then used to estimate the background rate of natural seismicity that represents a numerical expression of the expected likely future seismicity of the region and is consistent with the expected low strain rates. However, given that the island of Ireland is a low-seismicity region and that data are sparse, the calculated activity rates significantly overestimate the observed activity. Finally, a stochastic modelling approach was used to explore possible ground motions for realistic examples of small to moderate earthquakes that might occur in the island of Ireland.

1.3.4 Task 4: Assessment of the magnitude and physical effects of induced seismicity that may be associated with UGEE projects/operations in the island of Ireland

State-of-the-art developments in Coulomb rate-state (CRS) theory, together with Bayesian Monte Carlo (BMC) statistical methods, were applied to model and forecast the triggered seismicity surrounding a hydraulic fracturing operation.

The theoretical background of the forecast model was described and a CRS-based forecast implemented, based on non-ideal baseline estimates. Forecasts were derived for a series of scenarios defined with different reference activity levels and baseline network qualities. The implications for the nature of the uncertainties in the forecasts were illustrated.

1.3.5 Task 5: Technical specification for sub-regional seismic baseline monitoring

The main goal of seismic baseline monitoring is to establish the rate of naturally occurring seismicity in an area. Any seismicity induced in the future can then be quantified by comparing the seismicity recorded during the operational phase of a UGEE project with the baseline seismicity. In addition, a baseline study is useful to locate active faults and to map seismic noise levels in detail.

A detection threshold value of 0.5 ML (local magnitude) was chosen so that any induced seismicity is unlikely to be felt by humans or to cause any superficial structural damage; this is consistent with the limit recommended for cessation of injection in the UK traffic light scheme for fracking operations. Depending on hypocentral depth and local ground properties, in general, only events with magnitudes ≥ 2 ML are perceptible to humans and only events of ≥ 2.7 ML are thought to have the potential to cause minor damage.

Typically, observed seismic noise levels in Ireland were quantified and, from these, noise level detection threshold functions were determined as a function of seismic noise amplitude, ML and hypocentral distance. These calculated detection thresholds were compared with the actual detectability of local earthquakes by the Irish seismic networks, and it became clear that smaller local networks with interstation spacings of the order of 15 to 25 km are required to detect and locate all events with magnitudes ≥ 0.5 ML in the two study areas. The requirements that such local networks should meet were described.

1.3.6 Task 8: Examination of the global experience of seismic events stimulated by UGEE operations

This task provided an extensive review of induced seismicity in UGEE operations. This was compared with seismicity resulting from other activities, such as wastewater disposal in the central and eastern USA. Where possible, available UGEE data from recent examples, such as the induced seismicity in Blackpool, UK, as well as data from other analogous areas were used to investigate the factors controlling induced seismicity during fluid injection and to examine the relationships between injection volume and pressure, and induced seismicity. Finally, measures for mitigating the risk of induced earthquakes in energy technologies were reviewed and a number of recommendations were made specifically for UGEE operations in Ireland.

1.3.7 Task 9: Assessment of pre-fracturing modelling techniques

Fracturing generates microearthquakes. Tracking the location of these, using techniques from crustal seismology, allows the identification of the volume surrounding the perforation that is experiencing fracturing. Of course, each seismic event is extended in space, so fractures generated by microearthquakes extend beyond the fractured volume by an amount that is related to the location of the event and the fracture length producing it. The length is related to the magnitude, so knowledge of the location and magnitude of seismicity allows the estimation of the likely maximum extent of fracturing from the perforation.

This task surveyed published data on microseismicity surrounding UGEE perforations and described a stochastic approach, which, assuming the distribution of event sizes from other wells, allows modelling of the formation of fractures from widely accepted empirical scaling relations. Results are presented for a synthetic scenario and added to the statistics of seismicity data from North America. However, the modelling parameters leading to these results should be updated in near-real-time during any fracking operation.

2 Background

In conventional gas extraction, the gas pressure in the sub-surface and the permeability of the reservoir rocks allows gas to flow or be pumped to the surface through a well. Shale gas is a natural gas found in shale (a fine-grained sedimentary rock); however, the low permeability of shale means that gas will not flow when the reservoir is penetrated by a well. In unconventional gas extraction, hydraulic fracturing, or "fracking", is used to increase the permeability of the reservoir by creating networks of interconnected fractures and to improve the flow of oil or gas from rocks in the subsurface. The US National Research Council (NAS, 2012) reported that over 35,000 hydraulically fractured shale gas wells exist in the USA.

The unconventional exploration and extraction of gas must comply with all relevant requirements of EU legislation, as confirmed by a guidance note issued in 2011; this includes the Environmental Impact Assessment (EIA) Directive (2014/52/EU), which came into force on 15 May 2014.

UGEE operations and their associated potential impacts are currently undergoing assessment in various jurisdictions, including assessments by the US Department of Energy and in an initial European Commission assessment of hydraulic fracturing practices in the context of shale gas developments, which has identified a number of environmental areas potentially at risk from these practices; these risks include impacts on air quality.

In addition, a special report by the International Energy Agency (IEA) has stressed the need for robust and coherent measures in relation to UGEE operations, including: "full transparency, measuring and monitoring of environmental impacts" and has concluded that "governments, industry and other stakeholders must work together to address legitimate public concerns about the associated environmental and social impacts" of unconventional fossil fuel projects.

In nearly all countries with operational UGEE activities, shale gas extraction has proceeded without extensive baseline investigations being carried out. This lack of baseline monitoring has complicated the task of determining the range and magnitude of environmental impacts, including seismic impacts. Unlike many countries, the island of Ireland is in a position where extensive baseline studies and investigations can be completed in the absence of ongoing UGEE works and prior to any decisions being made as to whether or not UGEE operations should be permitted.

3 Definitions and Concepts – Seismology and Seismicity

This chapter explains key definitions and concepts relating to seismic events and UGEE used throughout this report.

3.1 What and Where

Earthquakes are the result of sudden movements along faults within the Earth that release stored-up elastic strain energy in the form of seismic waves that propagate through the Earth and cause the ground surface to shake.

The size of any earthquake depends on both the area of the fault that moves (ruptures) and also the amount of slip (or displacement) on the rupture plane. Earthquake activity is greatest at the boundaries between the Earth's tectonic plates. However, earthquakes can also occur within the plates far from the plate boundaries where strain rates are low. Ireland is situated in an intraplate location.

3.2 Measuring the Size of an Earthquake

Earthquake magnitude is a measure of the amount of energy released during an earthquake. Several different magnitude scales have been developed; however, the most standard and reliable measure of earthquake size is moment magnitude. The scale is logarithmic, so each whole-number increase in magnitude represents a 10-fold increase in measured amplitude and an approximately 32-fold increase in the energy released. Seismic moment is usually estimated directly from recordings of earthquake ground motions.

3.3 Behaviour in Space and Time

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, which relates the number of large events to the number of small events. In general, for each unit increase in magnitude, the number of earthquakes reduces 10-fold.

Although the probability of an earthquake at any given time is constant and independent of the time of the last event, they often occur in sequences that are clustered in space and time. The largest earthquake in such a sequence is known as the mainshock. The mainshock is followed by aftershocks, which occur due to readjustment to a new state of stress along the portion of a fault that slipped at the time of the mainshock. The pattern of the aftershock sequence depends on the size of the event and the local tectonic setting.

3.4 Types of Earthquakes Generated by Fracking

Fracking can potentially generate two distinct populations of earthquakes, which have different origins and present different hazard profiles.

1. As an essential part of the fracking process, cracks are generated in intact rock. Each new crack is essentially a brittle failure of the rock and seismic waves that travel outwards are generated causing the ground surface to shake where they impact on it. The energy for these events is almost entirely derived from the fluid injection process and therefore the largest potential earthquake that can be produced by this method is also strictly energy-limited. To date, it is thought that the maximum magnitude for events generated by this process is approximately 3 ML, though the largest earthquakes that have been experienced as a result of most fracking projects are considerably smaller.
2. High-pressure fluid injected into a rock mass also deforms the mass and produces stress changes within it. If the rock mass contains pre-existing faults, which most rock does, these stress changes may make such faults fail. There are two processes that contribute to this:
   - (a) Increasing the pore fluid pressure on a fault plane effectively reduces the stress that stops it from slipping; this can induce earthquakes.
   - (b) The deformation of the rock around the injection site changes the stress field for many hundreds of metres around the injection site

and, where this interacts with pre-existing faults, it can cause them to fail (or slip), generating an earthquake. Since the energy for these events comes largely from forces stored in the rock mass prior to injection, they do not have a well-defined maximum magnitude. While an increase in fluid pressure along the fault always makes it more likely to fail, stress perturbation can bring an existing fault either closer to or further from failure (it is not certain that a stress change as a result of fracking will generate triggered earthquakes). In addition, the probability that such an event is triggered depends strongly on the prior seismic activity of the area (these events are very unlikely in areas, such as Ireland, where the background seismicity is extremely low).

Within the Project A2 reports, events of the first type, which are an essential part of the rock fracturing process that releases the sought-after hydrocarbons, are called "fracked" events. Those that are generated on pre-existing faults, either by increased pore fluid pressure or by stress interaction, are called "triggered" events. All earthquakes generated by the fracking operation are described as "induced" earthquakes.

3.5 Geographic and Tectonic Context

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. Plate boundary zones include the margins of the Pacific and the collision zones between both India and Eurasia, and Africa and Eurasia. However, earthquakes can also occur within the plates far from the plate boundaries and where strain rates are low. Large areas of Asia, Australia, Europe and North America all experience intraplate earthquakes, although these events are relatively rare in comparison to seismicity events at plate boundaries.

The nearest plate boundary to Ireland lies approximately 1500 km to the north-west at the mid-Atlantic ridge. The north-east margin of the north Atlantic Ocean is passive and is characterised by unusually low levels of seismic activity in comparison to other passive margins around the world.

As a result of its geographic position, Ireland is characterised by low levels of earthquake activity and a low seismic hazard. Evidence for this comes from observations of earthquake activity dating back to the 14th century, which suggests that earthquakes felt by people are very rare (Figure 3.1).

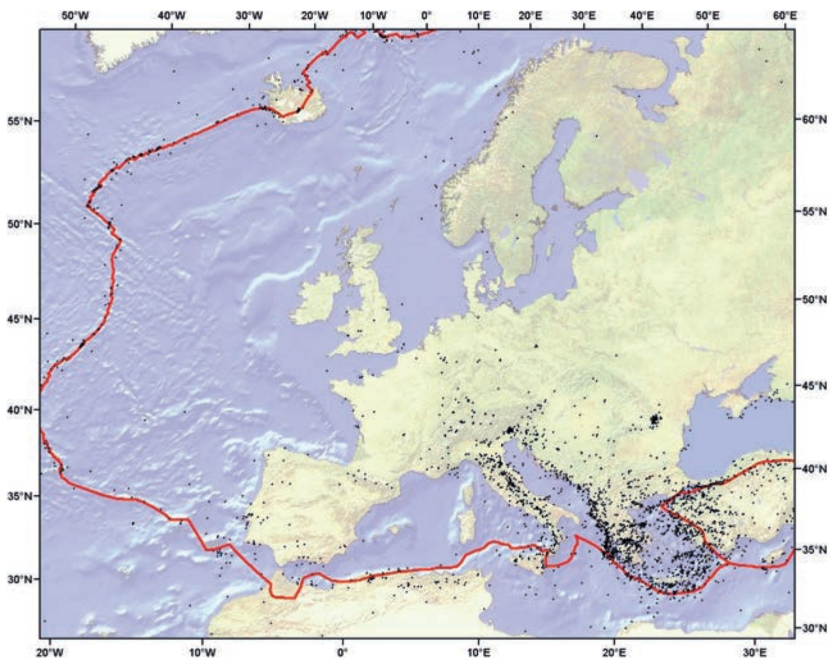

Figure 3.1. Distribution of earthquakes across Europe. Black circles show the distribution of earthquakes with a magnitude of greater than 5 across Europe. The red line shows the margins of the Eurasian plate. Most earthquake activity is located at the southern margin of the Eurasian plate in Greece and Italy, along the collision zone between Africa and Eurasia.

4 Assessment of Existing Baseline Monitoring Operated Worldwide for UGEE Projects/Operations (Task 1)

4.1 Introduction

Anthropogenic activity, such as underground mining, deep artificial water reservoirs, oil and gas extraction, geothermal power generation and waste disposal, can result in man-made or “induced” earthquakes. While generally small in magnitude in comparison with natural earthquakes, events are often still perceptible at the surface; a small number have been quite large with magnitudes greater than 5 Mw (seismic moment magnitude).

It is important to be able to discriminate between the naturally occurring, background levels of seismicity (which are typically relatively stable over time) and man-made seismicity (which varies more strongly with time). To do this, it is necessary to establish an accurate baseline of background earthquake activity. A change in seismicity rate has been observed in eastern North America over the past decade and has been linked to long-term disposal of large volumes of waste fluid in deep boreholes. Figure 4.1 shows that, after decades of a steady earthquake rate (average of 21 events/year), the number of observed earthquakes began to increase around 2001 and rose to 188 earthquakes in 2011.

Existing networks for regional monitoring are usually only reliable above a certain magnitude threshold (in many cases 2.0) and this is dependent on the number and distribution of sensors in the network. Therefore, smaller local networks of sensors are needed to reliably detect and locate smaller events and can also help to identify any seismogenic features, such as active faults, allowing them to be avoided during subsequent operations. However, until recently, baseline seismic monitoring at most UGEE sites has been almost unheard of, though this may change as a result of the induced earthquakes observed during hydraulic fracturing operations in the Etsho and Kiwigana fields in Horn River, Canada, and at Preese Hall, Lancashire, UK. The earthquake activity at Preese Hall resulted in a UK-wide suspension of fracking activity and considerable public concern

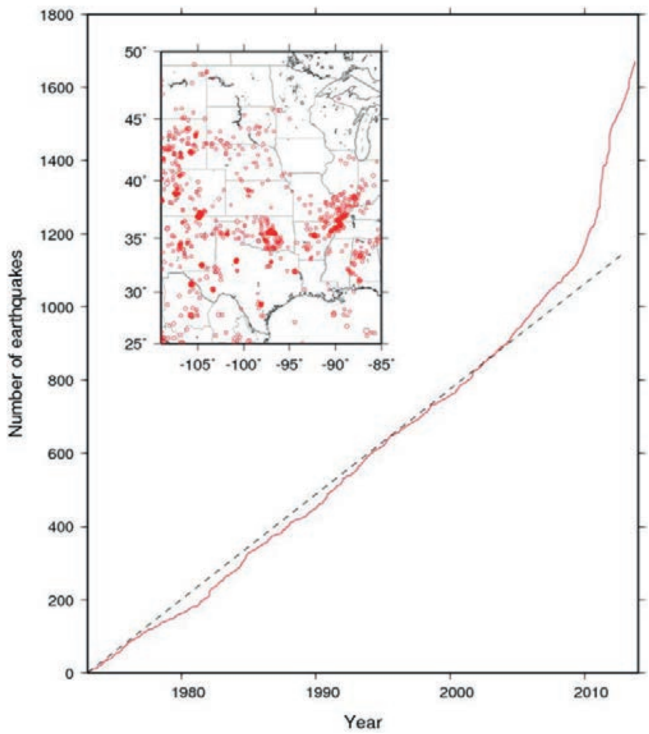

Figure 4.1. Cumulative count of earthquakes with moment magnitude M≥3 in the central and eastern USA, in 1967–2012 (from Ellsworth, 2013). Reproduced with permission from the American Association for the Advancement of Science.

about potential seismic impacts. A review by the Royal Society and the Royal Academy of Engineering into the risks associated with hydraulic fracturing suggested that monitoring should be carried out before, during and after shale gas operations to inform risk assessments (Royal Society and Royal Academy of Engineering, 2012). The subsequent regulatory roadmap published by the Department for Energy and Climate Change in the UK includes specific measures for the mitigation of induced seismicity and requires any operators using hydraulic fracturing to monitor seismic activity before, during and after fracturing (Department for Business, Energy & Industrial Strategy, 2015).

4.2 Required Durations of Monitoring Earthquake Frequency Magnitude Relationship

Current best estimates of the seismicity rate across Ireland and the surrounding offshore area are low, in keeping with the low numbers of observed earthquakes. Scaling these rates to the study areas suggests that there would be an earthquake with a magnitude of 2 or greater approximately every 60 years in the larger of the two study areas, and even fewer earthquakes in the smaller study area. The low expected seismicity rate presents a significant challenge for this project, since it may require a relatively long period of baseline monitoring to fully characterise the rates in each of the two study areas, if the levels of natural seismicity are as low as expected from the available historical and instrumentally recorded data.

4.3 Earthquake Detection and Location

Reliable and uniform detection of seismic events across a given area of interest requires a uniform distribution of monitoring stations. The density of the stations, along with the noise levels at each station, determine the lowest magnitudes that can be reliably detected. Higher station densities will be required to detect and locate lower magnitude events. Noise levels at individual stations also affect detection capability and these should be low to maximise detection potential. A monitoring network must also extend beyond the boundaries of the area of interest to be able to reliably detect earthquakes that occur close to these limits. Detection capability for different station distributions and densities can be readily modelled using a number of relationships that determine the amplitude of seismic waves as a function of magnitude and distance.

Reliable location and magnitude measurement places additional constraints 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. Large errors are likely to limit the capability to discriminate between induced and natural earthquakes. Again, a uniform station density is required to ensure comparable location accuracy across the region of interest, with monitoring stations extending beyond the area of interest.

The installation of sensors in boreholes significantly improves signal-to-noise ratios, which is critical for recording high-quality data and for the detection and measurement of small earthquakes. Borehole arrays are likely to offer significantly better performance than surface instruments and the use of such arrays has become standard practice for the operational phase of many geothermal projects and for microseismic monitoring in the UGEE operations.

4.4 Baseline Monitoring in the Geothermal Industry

Seismic monitoring is widely used in the geothermal industry before, during and after operations. Site-specific monitoring systems 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 (approximately 100 to 2000 m). Since most geothermally induced seismicity is below magnitudes of approximately 2.0, it is important to know the baseline level of seismicity at lower moment magnitudes (M) (M = 0 to 1) for active seismic zones to be properly identified.

4.5 Monitoring Case Studies

Data from four geothermal, mining and UGEE monitoring case studies in the UK and Switzerland have been presented, describing the monitoring networks and earthquakes detected. These case studies highlight the importance of an appropriate monitoring network for the reliable detection and location of any seismic events before, during and after operations that may induce seismic activity. In particular, the example of the seismicity induced by hydraulic fracturing at Preese Hall, near Blackpool, in 2011 shows how local monitoring stations are essential to reduce uncertainty and allay public concern.

4.6 Monitoring Hydraulic Fracturing Growth in UGEE

Microseismic mapping of hydraulic fractures is widely acknowledged as the best means of characterising stimulated fracture networks in unconventional reservoirs. Large quantities of microseismic data collected over the past decades, mainly in North America, has transformed our understanding of how these fracture systems grow in the sub-surface.

More recently, horizontal arrays deployed at the surface, or in shallow boreholes, have been used as an alternative to vertical borehole arrays and, although signal-to-noise ratios are generally lower, the lateral location accuracy of the events is increased without any measurement bias.

4.7 Conclusions

Several conclusions can be drawn from this assessment of baseline monitoring in relation to UGEE projects and operations undertaken to date in other parts of the world.

Baseline monitoring should be an essential requirement for any future UGEE activities for the reliable characterisation of background levels of seismicity and the identification of any unusual seismicity or active faults. Baseline monitoring is also essential for distinguishing any induced earthquakes from natural background earthquake activity.

Baseline monitoring must be established prior to the commencement of any activity that is known to induce earthquakes. The duration of monitoring will depend on both the state of existing monitoring and the natural earthquake activity rates, since areas with higher activity rates will require shorter periods of monitoring. The estimates of activity rates in the two study areas described in this report demonstrate that detection thresholds will need to be low and that a relatively long period of study may be required to fully characterise seismicity in these areas. Detailed monitoring will also be required in each study area to test the assumption of uniform seismicity rates across Ireland and detect any unusual seismicity. The higher the level of seismic activity in the areas, the shorter the period of monitoring that would be required to establish accurate baseline levels of seismic activity (and vice versa).

A uniform distribution of monitoring stations is required for the reliable and uniform detection of seismic events and for comparable earthquake location accuracy across the region of interest. Higher station densities will be required to detect and locate lower magnitudes. The requirements for reliable location and magnitude measurements place additional constraints on network design, since measurements at more stations are needed than for detection alone, and monitoring sites located outside the study area are also required.

Extensive experience of seismic monitoring in the geothermal industry may be considered as best practice for UGEE.

5 Evaluation of Methodologies for the Monitoring of Ground Deformation That May Be Associated with UGEE Projects/Operations (Task 2)

5.1 Introduction

The aim of this task was to evaluate methodologies for monitoring ground deformation that may be associated with UGEE activities. It is important to monitor the surface motion quantitatively in order to gauge potential damage to structures and to address the potential concerns of the public and policymakers.

Existing mature technologies that can measure ground motion at a point in space include:

- geodetic sensors, such as GNSS, sometimes referred to as the Global Positioning System (GPS), which record georeferenced displacements or movements in one, two, or three dimensions;
- geotechnical sensors, such as tiltmeters, located at the surface or in boreholes, which are used to measure non-georeferenced displacements or movements.

The use of integrated GNSS and/or tiltmeters is common practice for successful ground motion monitoring in many applications, although there is little published evidence of their application in UGEE projects/operations, or, in fact, of the magnitude and geographical distribution of ground deformation associated with UGEE operations worldwide. The application of *in situ* point measurement sensors for ground deformation monitoring is already described in published literature; therefore, this report focuses on the application of radar interferometry from satellites in the island of Ireland. As well as the regional coverage afforded by InSAR, this technique also benefits from an archive of data from 1992, which can be used to gain otherwise unavailable baseline information.

InSAR monitoring is generally applied to urban areas (due to the presence of abundant reflectors); therefore, the application of this technique to monitor potential ground deformation in non-urban areas of Ireland was the primary aim of this task.

5.2 Methodology and Results

The three main factors affect whether or not InSAR can be successfully undertaken:

1. availability of satellite radar data;
2. visibility of the terrain by the satellite sensor;
3. presence of scatterers.

5.3 Availability of Synthetic Aperture Radar Data

Each time the radar satellite passes overhead, it captures an image of the ground. Multiple images of the same location over a period of time provide a time-series showing the elevation of the terrain; therefore, it can be determined whether the ground is stationary, subsiding or uplifting. If processed appropriately, the imagery can also be used to determine lateral motion. Greater numbers of images result in higher accuracy of measurement of ground motion and at least 15 to 20 images of the same acquisition geometry (i.e. the same mode, orbit and track) are required to undertake a multi-interferogram InSAR analysis.

There are several radar satellites currently in orbit that acquire suitable imagery and there are large archives of their imagery for Ireland. These archives are vitally important, because they can be used to “go back in time” to 1992 (when they first started operating) to create a baseline of ground motion. This archive suggests that multi-interferogram InSAR analysis should be possible for the island of Ireland. Nevertheless, further analysis of the normal and temporal baselines of the images is needed to verify whether or not interferometric phase correlation can be guaranteed.

The European Space Agency (ESA) launched the satellite Sentinel-1A in April 2014; Sentinel-1B is due for launch in 2016. While there is not currently a sufficient volume of Sentinel-1A data for Ireland to undertake

InSAR analyses, the catalogue is growing and these data were available for ongoing ground motion projects by the end of 2015.

5.4 Visibility of the Terrain by the Satellite Sensor

Radar satellites have a sideways view of the Earth's surface and are therefore prone to geometric distortions; in addition, there can be radar shadows in areas of high relief, making some areas invisible to the sensor. The EU Digital Elevation Model (DEM) at 25 m-resolution (Figure 5.1) was utilised to model terrain visibility analysis for Ireland.

It was found that most of the landmass (>99.9%) is visible to the radar sensor in at least one acquisition mode, bearing in mind that distortions in hilly areas can be compensated for by using either ascending or descending orbits.

5.5 Presence of Scatterers

A persistent scatterer (PS) is a location on the ground that maintains coherence through several radar images; these are required for point-based InSAR analyses. The ability of surface targets to operate as PSs is related to ground properties, such as geometry and land cover.

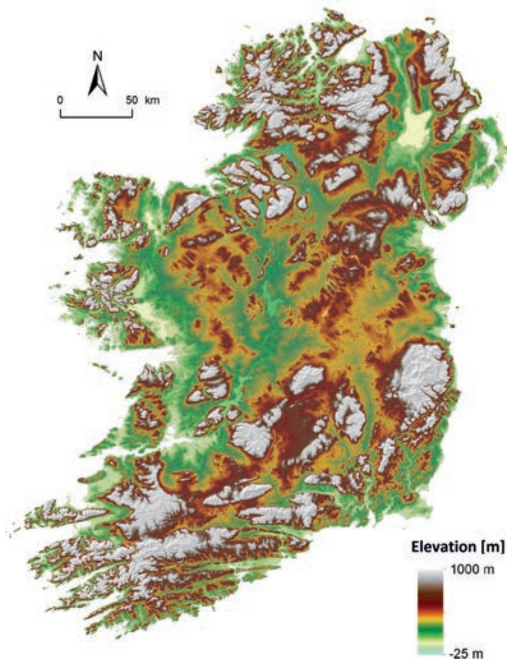

Figure 5.1. The EU 25 m-resolution Digital Elevation Model (produced using Copernicus data and data from research funded by the European Union).

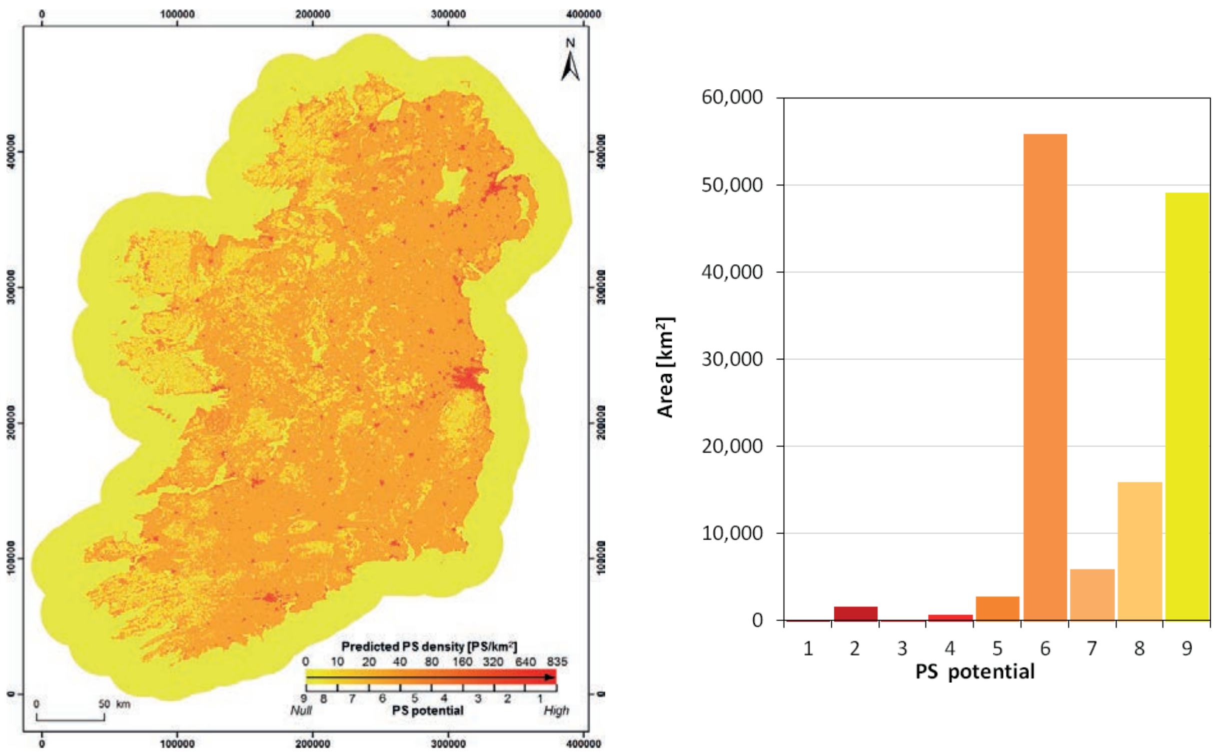

Figure 5.2. Modelled potential for persistent scatterers in Ireland.

A British Geological Survey (BGS) feasibility study in Britain used PS datasets for quantitative calibration of the Co-ordination of Information on the Environment (Corine) land cover data and derived the relationship between the cover types and the numbers and locations of the PSs. The same relationship was used to model the occurrence of PSs in Ireland using the Corine land cover data. Urban and rocky terrains have a higher likelihood of providing reflectors (Figure 5.2); however, over 90% of Ireland falls into land cover types that are predominantly rural and therefore the use of the InSAR technique would only be partly successful. Nevertheless, this does not mean that all forms of synthetic aperture radar (SAR) would be unsuitable in these locations. The British Geological Survey is currently utilising other techniques, such as Intermittent Small Baseline Subset (ISBAS) in British non-urban environments, which is providing very positive results. For example, InSAR analysis in South Wales using the ISBAS technique increased the number and density of scatterers by a factor of approximately 3.4 compared with conventional Small Baseline Subset (SBAS) analysis, offering significant advantages for the interpretation of ground motion.

5.6 Recommendations

Ground deformation as a result of UGEE projects/operations will not necessarily result in damage to structures, but it is important to monitor the motion at surface quantitatively in order to gauge potential damage to structures and to address potential concerns of the public and policymakers regarding impacts on the environment. This technique of ground motion measurement has been used for this purpose in post-mining areas.

It is recommended that any UGEE projects operating in Ireland should be monitored using historical and current satellite radar data, processed to provide InSAR results using a technique such as ISBAS. The historical data will provide a baseline defining the stability of the surface prior to any UGEE operations. Satellites such as Sentinel-1A are currently acquiring radar data that could be used for ongoing monitoring.

In combination with the InSAR technique, complementary *in situ* methods such as GNSS and tiltmeters could be deployed; integrating the monitoring techniques provides better and more detailed information on deformation characteristics.

6 Assessment of Existing Data on Natural Seismicity in the Island of Ireland (Task 3)

6.1 Introduction

Ireland lies at the north-west margin of Europe, adjacent to the continental shelf and is a region of low seismic activity. This lack of seismic activity in Ireland has been demonstrated by both historical observations and modern instrumental recordings, which show that recorded levels of seismic activity in Ireland are significantly lower than in Britain, despite a similar geology.

This study provided an updated review of earthquakes in Ireland. Historical data from a number of available sources has been combined with modern instrumental data to construct a single coherent catalogue with a uniform moment magnitude scale. This catalogue has then been used to estimate the background rate of natural seismicity that is a numerical measure of the expected future seismicity of the region and is consistent with the expected low strain rates. Two catalogues of completeness relationships were used to estimate activity rate, each with different magnitude of completeness thresholds used for different time intervals.

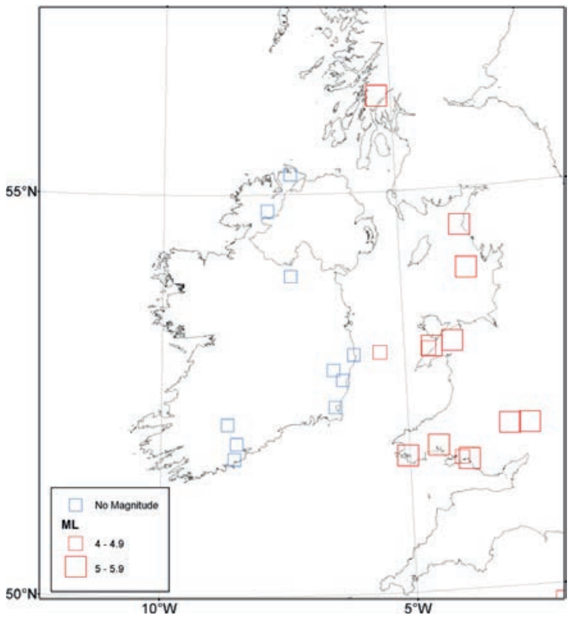

Figure 6.1. Historical earthquakes felt in Ireland (from Richardson, 1975). The red squares show events with local magnitudes assigned from Musson (1994). The blue squares show events for which no magnitude has been assigned.

6.2 Data

Historical accounts of seismic events felt in Ireland amount to only 26 events in the interval 1500–1970 that can be deemed credible (Figure 6.1). Of these, half of the accounts can be attributed to earthquakes that occurred outside Ireland in England, Scotland or Wales. These were nearly all events of around magnitude 5 ML or above that occurred in western Britain and were widely felt across Britain and Ireland. The other 13 events occurred in Ireland and the immediate offshore area.

Earthquake intensity, a qualitative measure of the strength of shaking of an earthquake determined from the observed effects on people, objects and buildings, can be determined from historical accounts of earthquakes and used to estimate an earthquake location and magnitude. The results suggest that the 13 events in Ireland had low intensities and were only felt over small areas, suggesting that these were small earthquakes. Magnitudes have not been determined for these historical Irish earthquakes, except for the magnitude 4.4 ML earthquake in the Irish Sea in 1951, for which instrumental data from the seismograph at Rathfarnham Castle was available. In addition, the locations remain uncertain, as they were assigned directly to the area of maximum perceived intensity. These historical earthquakes in Ireland correspond to three areas: east coast (Wicklow, Wexford and the Irish Sea), north (County Donegal), and south coast (around Cork). Given the high standard of historical records in the period in question, it seems very unlikely that any significant earthquakes remain undiscovered.

Instrumental data from the Dublin Institute of Advanced Studies (DIAS) and BGS catalogues (Figure 6.2) confirm these low rates of seismic activity. Ireland had at least one operational seismograph throughout the 20th century and the first seismograph network was installed in 1977. These networks successfully detected and located a number of earthquakes in the

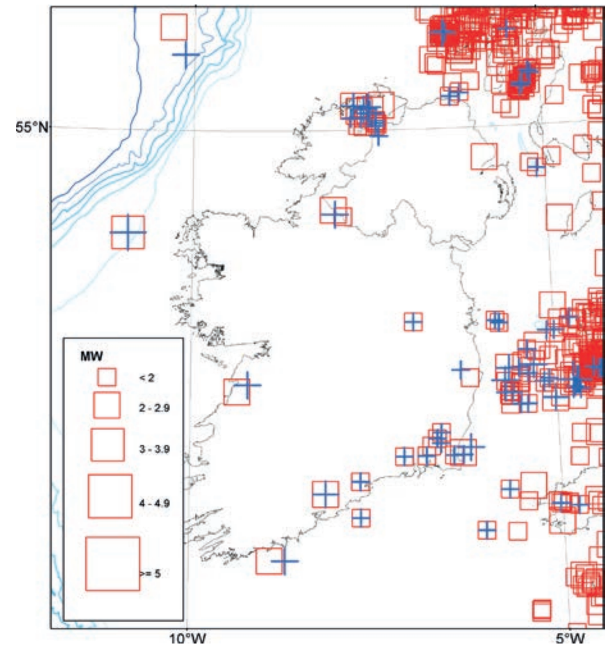

Figure 6.2. Instrumentally recorded seismicity in Ireland and Britain from 1970 to present. Data are from the Dublin Institute of Advanced Studies catalogue (blue crosses) and the BGS catalogue (red squares). Symbols are scaled by magnitude, as indicated.

period 1980 to present. More earthquakes would have been detected had the limits of detection been lower. Almost all this measured seismicity has been found in areas where historical earthquakes have occurred: east coast (Wicklow, Wexford and the Irish Sea), north (County Donegal), and south coast (around Cork). The exception to this is the magnitude 4.0 ML earthquake off the coast of County Mayo in 2012, which is the largest Irish event in the catalogue. It is also notable that nearly all the seismic activity in Ireland, both modern and historical, is concentrated around the coast and there is an almost complete absence of seismicity inland, with only two earthquakes recorded by modern instruments in County Leitrim.

6.3 Tectonic History

Present day tectonic deformation in Ireland appears to be dominated by forces generated at the mid-Atlantic ridge and, to a lesser extent, by forces resulting from the collision of Africa with Europe. A secondary source of crustal stress in the north of the island of Ireland may be glacio-isostatic adjustment (GIA), resulting from the disappearance of the British–Irish ice sheet.

No Irish or British earthquake, recorded either historically or instrumentally, has produced a surface rupture, and typical fault rupture lengths for the largest recorded British earthquakes are of the order of 1–2 km with a slip of around 10 cm. Focal mechanisms determined for British earthquakes show fault planes that are broadly sub-parallel to either a north–south or east–west direction. These appear to be favourably oriented for reactivation under the existing north-west south-east maximum horizontal stress directions.

6.4 Earthquake Activity Rates

Earthquake catalogues can be used to estimate seismic activity rates over long periods. However, determining both the activity rate and proportion of large events in relation to small events can be problematic when the total number of events is small. In addition, the number of earthquakes at lower magnitudes is often underestimated in many earthquake catalogues, as a result of the inability to detect smaller events. This leads to the concept of a completeness magnitude, which can be defined as the lowest magnitude at which 100% of the earthquakes in a space–time volume are detected.

All the seismicity contained within the seismic source zone for Ireland used in the recent EU SHARE (Seismic Hazard Harmonization in Europe) project was used to estimate the earthquake activity rate for this region. Two different catalogue completeness relationships were considered, each with different magnitude of completeness thresholds used for different time intervals.

The use of the catalogue completeness relationship for offshore areas around Britain suggests that there should be an earthquake with a magnitude of 4 or above approximately every 70 years. However, this would lead to significantly more earthquakes than are currently observed in Ireland. Using the same catalogue completeness relationship as that for England, Wales and Scotland suggests that there should be an earthquake with a magnitude of 4 or greater approximately every 476 years, which agrees more closely with the observed data.

6.5 Possible Ground Motions for Small and Moderate Earthquakes

Accurate assessment of seismic hazards 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 hazards, ground motions are commonly estimated using empirical ground motion prediction equations (GMPEs). An alternative is to simulate ground motions using a numerical method, such as stochastic modelling based on the earthquake source parameters as well as parameters to characterise path and site effects. *Final Report 2: Baseline Characterisation of Seismicity* uses this approach to explore possible ground motions for small to moderate earthquakes that might occur in Ireland and were then compared with existing regulations for vibrations from blasting in the UK.

From the historical and instrumental earthquakes recorded, it is clear that earthquakes are confined within the thickness of the crust, with most earthquakes occurring at depths of between 5 and 20 km. In contrast, earthquakes induced by anthropogenic activities often occur at very shallow depths. 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 6.3 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. These can be compared with the limits for levels of ground vibrations caused by blasting set out in the British Standards BS 6472-2 and BS 7385-2 and shown by the grey dashed lines in Figure 6.3. BS 6472-2 sets limits for acceptable levels of ground vibrations caused by blasting at 6–10 mm/s during the working day, 2 mm/s at night and 4.5 mm/s at other times. BS 7385-2 specifies limits for vibrations caused by blasting, above which cosmetic damage could take place. These are 15 mm/s at 4 Hz, increasing to 20 mm/s at 15 Hz and 50 mm/s at 50 Hz.

Earthquakes with magnitudes of 4.0 or above may approach the limits for cosmetic damage set out in BS 7385-2 but this is generally only at hypocentral distances of less than 10 km. Smaller earthquakes, with magnitudes of 3.0, may also exceed the limits for vibration set out in BS 7385-2, though only at very small distances from the earthquake source, for example less than a few kilometres. Smaller earthquakes may also result in ground velocities that exceed the limits set by BS 6472-2, particularly the night-time limit of 2 mm/s. While the modelled ground motion shown here should be considered as only indicative, there is good general agreement between the calculations and many observations of small earthquakes in the UK.

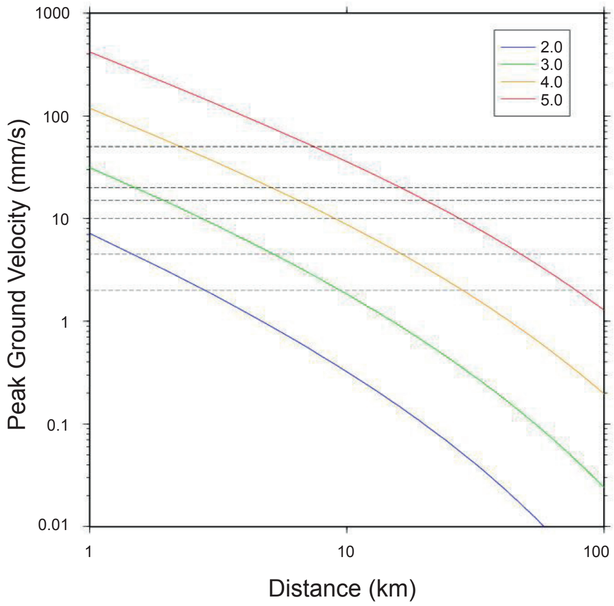

Figure 6.3. Modelled peak ground velocity (solid coloured lines) plotted as a function of hypocentral distance. The grey dashed lines show the limits for acceptable vibrations from blasting as specified in BS 6472-1 and BS 7385-2.

6.6 Public Perception of Potential Damage from Earthquakes

While there has been some research undertaken on assessing the public perception of shale gas extraction in the UK, very little documented evidence exists of the public perception of seismic activity itself.

Nottingham University has undertaken 10 surveys of public perception of fracking since March 2012. The possible link between fracking for shale gas and earth tremors has triggered considerable concern and is viewed by some as a potentially dangerous and damaging impact of shale gas exploration.

An online study by Cardiff University on public attitudes to fracking, which used a large and diverse sample, found a relatively high level of ambivalence towards fracking, with minor tremors ranking 13th as an issue of concern behind other risk factors.

6.7 Conclusions

A review of published data confirms that earthquake activity in Ireland is very low. Nearly all the recorded seismic activity in Ireland, both instrumental and historical, is concentrated around the coast and there is an almost complete absence of seismicity inland.

Calculated earthquake activity rates for Ireland were found to vary depending on the assumed level of completeness of the earthquake catalogue. The use of the same catalogue completeness thresholds as for Britain suggests that there should be an earthquake with a magnitude of 4 Mw or greater, somewhere in Ireland and the surrounding offshore area, approximately every 476 years. This is in reasonable agreement with the observed data. However, the use of a more conservative estimate of catalogue completeness predicts a higher activity rate, which would lead to significantly more earthquakes than currently observed. This highlights the problem of estimating reliable rates in low-seismicity regions that allow seismic hazards to be reliably quantified.

The average activity rate for Britain suggests that there should be an earthquake with a magnitude of 4 Mw or greater approximately every 6 years. The reasons for this dramatic difference remain poorly understood, given the geological and tectonic similarity between Ireland and Britain.

Modelled ground motions for earthquakes with moderate magnitudes, such as might occasionally occur in or around Ireland, suggest that ground velocities are unlikely to exceed typical levels at which cosmetic damage might occur, except close to the earthquake source.

7 Assessment of the Magnitude and Physical Effects of Induced Seismicity That May Be Associated with UGEE Projects/Operations in the Island of Ireland (Task 4)

7.1 Introduction

No satisfactory deterministic model for forecasting fluid-induced seismicity exists; therefore, a modelling approach was developed for monitoring and short-term forecasting of fluid-induced seismic sequences. This model was then used to illustrate the importance of uncertainty in forecasting such non-linear processes in complex systems and to assist in the development of appropriate baseline and ongoing monitoring.

The forecasts were based on the CRS formulation, which models triggered seismicity in terms of the amplification by stress perturbations (i.e. from the fluid injection) of pre-existing background seismic activity. The forecast relies on a high-quality model for the background seismic activity and a robust estimate of the stress associated with the injection process.

The essential scientific background was reviewed and a detailed description given of the theoretical and statistical elements of the algorithm, particularly including the quantification of the associated uncertainties. The chosen input parameters of the simulation are necessarily arbitrary and hypothetical at this stage; the software was designed as a generic tool that could be applied to any injection scenario (i.e. not limited to hydraulic fracturing).

7.2 Theoretical Background

There are a number of other features of aftershock distributions that are not predicted by the simple static stress model. These include the dependence of the spatial distribution of triggered seismicity on the distribution of previous activity in the region and the time-dependence of the rate of triggered events, which has been determined empirically to decay as a power-law with time following the main shock (Omori-Utsu decay). CRS models, in which the static stress acts on a population of faults with rate- and state-dependent frictional properties, have been shown to reproduce some of the temporal and spatial characteristics of aftershock distributions of tectonic earthquakes. Since CRS can be extended to model rate changes from an arbitrary time-varying stress field, the model therefore has the potential to provide a framework for quantitative forecasting of rates of seismicity induced from fluid injection.

Coulomb stress perturbations may be calculated provided that the time-varying pressure field resulting from the flow of injected fluid through the pore spaces is known. There are two elements to this problem: modelling fluid flow in a complex medium, i.e. a porous rock volume with heterogeneous permeability, and coupling this flow to the rock itself, so that the time-dependent pressure results in realistic deformation of the medium.

The basic method for solving the fluid flow problem is the "lattice gas" model, which is based on simple rules for the microscopic movement and interaction of particles on a lattice, and, at the macroscopic scale, it has been found to reproduce the Navier-Stokes equations for the motion of viscous fluids.

7.3 Discussion

In the absence of any available and reliable models for forecasting seismicity caused by hydraulic fracturing, a rigorous statistical forecast model has been developed based on state-of-the-art understanding of induced seismicity. The model presented here is newly developed and will undergo further statistical evaluation. Some important general features of the results may be identified.

The uncertainties presented in the report mean that robust estimates for basic hazard parameters are likely to be high in an area of very low seismicity; this will be the case even for the most realistic baseline. High completeness thresholds for the networks and low underlying seismicity rates both contribute to high levels of uncertainty; they are both likely to be significant problems in applying any statistical forward modelling in the Irish context.

The use of a homogeneous reference catalogue generates systematic errors in the parameter estimates and will in general lead to moderate over-prediction of rates. This problem can be minimised (but not solved) by high-quality baseline deployment and data analysis to generate the best reference model possible. However, ultimately, detailed subsurface structural information will be required to understand this problem completely.

The model does not include uncertainties in earthquake locations and magnitudes or, for example, uncertainties in any of the model parameters, such as the fault frictional constants. While these errors are considered to be relatively minor compared with the other issues discussed, every effort to minimise them should be made based on the best seismological and structural data available. Any remaining uncertainties can then be incorporated into the Monte Carlo sampling analysis to estimate their effect on the forecast.

The data requirements for high-quality forecasts are significant and the specifications of baseline networks are subject to external considerations; whether or not it will be possible to constrain the uncertainties enough for acceptable forecasting will probably only be known after preliminary seismic data has been collected, which will provide better knowledge of underlying ambient seismicity rates in Ireland.

7.4 Conclusions

Task 4 has several important implications for baseline and production monitoring:

1. The choice of fault network model has a first-order effect on the success of the seismicity forecasts. It is recommended that information on the active structure is obtained from detailed structural studies and also from any available high-quality focal mechanisms of well-recorded earthquakes in the area.
2. Robust forecasts of the hazard-relevant parameters of induced earthquake catalogues can only be made using a high-quality network and current best practice in data analysis; a high-quality seismic network with good location capabilities, state-of-the-art data analysis and a low completeness magnitude is essential during the baseline monitoring phase. This should be augmented by denser local networks, possibly including borehole instruments, deployed during extraction operations
3. Significant systematic errors are introduced into induced rate estimates by assuming homogeneous reference rates. Networks should ideally be designed to resolve heterogeneous baseline rates in detail. However, statistical models for fault distributions in the region would potentially allow these uncertainties to be estimated, using an extension of the Monte Carlo methodology employed here.
4. Current catalogues are completely inadequate for forecast modelling on the spatial scales of the study areas and to the standard required for this application. In this report, the use of synthetic catalogues to represent hypothetical baseline scenarios are used to illustrate the nature of the uncertainties that might be expected, but this does not allow specific forecasts from an injection event to be made at present.

Finally, perhaps the most important general conclusion is that the low background rates of seismicity observed in current Irish catalogues have two contrasting implications:

1. From a scientific perspective, the data are unlikely to allow robust forecasts of the main parameters.
2. In terms of impacts, it means that hydraulic fracturing projects in Ireland are extremely unlikely to have any potentially troublesome seismic consequences; however, this conclusion will require confirmation by examination of high-quality baseline catalogues.

8 Technical Specification for Sub-regional Seismic Baseline Monitoring (Task 5)

Detailed descriptions of this work are presented in *Final Report 2: Baseline Characterisation of Seismicity*. The aim of this task was to answer the following two questions:

- Is the detection threshold of existing seismic networks in Ireland sufficient to detect and to determine the location and magnitude of all local earthquakes with magnitudes ≥0.5 ML in the two study areas?
- What kind of local seismic network is required if existing seismic networks in Ireland are insufficient for baseline monitoring of all local earthquakes with magnitudes ≥0.5 ML?

The detection threshold value of 0.5 ML was chosen to allow detection of earthquakes at least one order of magnitude smaller than those that are typically perceptible to people. This is consistent with the limit recommended for cessation of injection during hydraulic fracturing in the UK, as specified in the regulatory roadmap published by the Department for Energy and Climate Change.

Seismic data from the Irish National Seismic Network (INSN) and the Science Foundation Ireland-funded University College Dublin (UCD) project Wave-Obs were available to this study. The seismic station locations of the two networks are shown in Figure 8.1. All regional epicentre locations are also shown for the period October 2011 to September 2014.

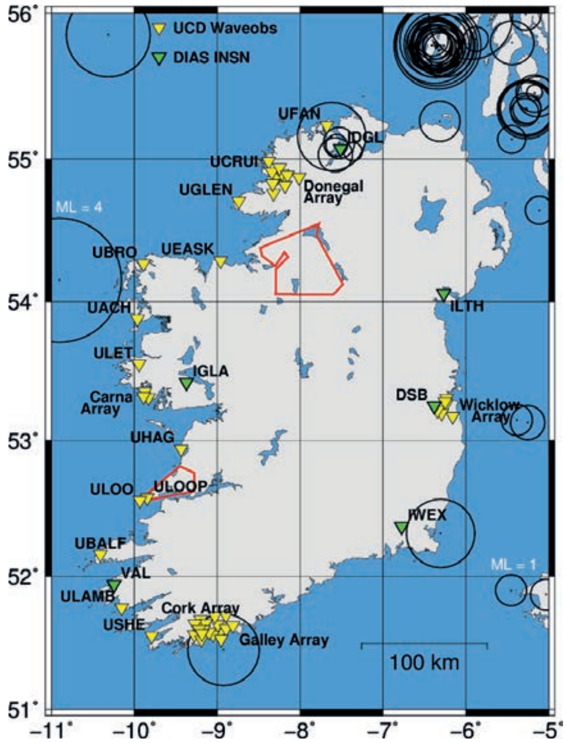

Figure 8.1. Map showing seismic station locations (triangular markers) from which data were available for this study. The black dots show earthquake epicentres for the period 1 October 2011 to 30 September 2014, with circle diameters proportional to magnitude; see labels for examples of earthquakes with magnitudes of 1 ML and 4 ML. The approximate locations of the two study areas are indicated by the red polygons.

8.1 Quantification of Seismic Noise Levels in Ireland

Seismometer recordings are a function of ground vibrations at the installation site and of instrumental noise. The ground vibrations are a mixture of continuous signals and event signals, such as earthquakes and explosions. Because continuous signals can mask the detection of event signals, they are often referred to as seismic noise. Seismic noise varies in amplitude and frequency content and is best quantified in the frequency domain.

8.2 Calculation of Earthquake Detection Thresholds

The local magnitude (ML) of earthquakes is defined as a function of the hypocentral distance, maximum ground displacement amplitude, geometrical spreading, attenuation and base level. The last three parameters depend on local conditions; for regions with similar attenuation characteristics, these parameters are similar and, therefore, the ML scale defined for the UK was adopted for Ireland in this study, as the geological setting is similar.

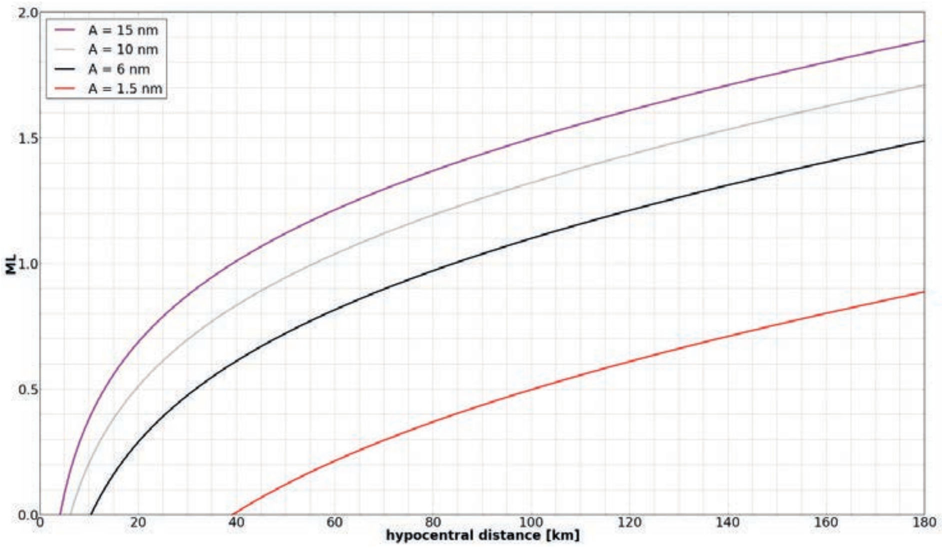

Figure 8.2. Magnitude (ML) plotted against hypocentral distance (R) for different maximum earthquake amplitudes A.

Figure 8.2 shows that the same maximum event amplitude *A* can be caused by earthquakes with different magnitudes *ML* and different hypocentral distances *R*. Figure 8.2 also shows that at a fixed hypocentral distance larger magnitude earthquakes cause larger ground displacements. It is usually assumed that a signal-to-noise ratio (SNR) of three is sufficient for earthquake detection and location. Therefore, the curves in Figure 8.2 also provide information on the smallest earthquakes that can be detected in environments with different background noise levels.

8.3 Comparison Between Calculated and Observed Detection Thresholds

The next step was to identify the maximum hypocentral distance at which high-quality seismometer installations in the two study areas can reliably detect all events with a magnitude ≥0.5 ML. To do this, five earthquakes with epicentres in County Donegal and local magnitudes between 0.6 and 2.2 were analysed for the epicentre locations. High noise levels can affect event detection, and the effect of high noise levels on event detection was demonstrated with recordings from the earthquake with a magnitude of 2.2 ML. This event occurred during a storm and it was shown that noise levels are especially high for stations close to the Atlantic coast. This is relevant to this study, because both study areas are located on or close to the west coast. In Ireland, seismic noise in the frequency band 1–2 Hz is generally elevated in coastal zones, especially on the western seaboard. In order to obtain noise levels not much higher than 1 nm, seismic stations in the baseline study should be located at least 4 km from coastlines directly open to the Atlantic Ocean. *Final Report 2: Baseline Characterisation of Seismicity* presents other examples of signal-to-noise ratios from the Wave-Obs study.

8.4 Influence of Installation Details on Observed Detection Thresholds

Further earthquakes with suitable hypocentral distances and magnitudes (with epicentres in Scotland and Wales) were analysed to provide more detectability observations. Generally, theory and observation were found to agree well, especially for magnitudes smaller than 1.6 ML.

Theoretical detection thresholds based on the UK ML scale were determined as suitable for the calculation of the location capability of the proposed baseline network geometries. These calculations require expected station noise levels as an input. Temporary Wave-Obs installations, with seismometers installed either in outbuildings and domestic garages or in field vaults, are of lower quality than permanent installations (which are housed in concrete vaults). However, the stations deployed inland and in larger bins can detect observed noise amplitudes almost as well as INSN installations, which can detect average noise levels of approximately 0.5 nm. Therefore, the construction of concrete vaults to house seismometers is not necessary to reach the requirement for measured noise amplitude levels.

8.5 Local Seismic Network Specifications

8.5.1 Deployment length

The reliability of the obtained seismicity rate depends on the number of earthquakes recorded, which, in turn, depends on the sensitivity of the network and the monitoring period. The seismicity rate in the Northwest Carboniferous Basin (NCB) is expected to be less than one event with a magnitude of 0.5 or larger every 2 years, with the Clare Basin (CB) rate estimated to be one fifth of that. These rates are so low that reliable estimation of the rates could not be achieved, even with a monitoring period of several decades; however, monitoring for at least 2 years could ascertain whether or not there is any unexpected seismicity in the study areas.

8.5.2 Network geometry

The determination of station density depends on the required magnitude detection threshold and the number of earthquake station records required for estimation of earthquake location and magnitude. The determination of earthquake location and magnitude requires signal detection by at least three stations; however, detection by more stations is preferred for improved accuracy.

In order to design suitable example network geometries, the following assumptions were made:

- The Richter relationship between magnitude and hypocentral distance for the UK was applied.
- Earthquake recordings with a signal-to-noise ratio of at least 3 are required by a minimum of six stations.
- Root mean square (rms) noise amplitudes at the stations are 1–2 nm (reflecting the relatively high noise levels expected for high-quality installations only during windy or stormy weather conditions).

The NCB study area was divided into equally sized triangles and the size of the triangles (station density) varied until a detection threshold of at least 0.5 ML and good detectability on the fringes were achieved. Satellite imagery was used to confirm that potential locations were not obstructed by lakes, towns or other large-scale structures and locations were revised accordingly.

The resulting example network has an interstation spacing between 15 km and 25 km. Figure 8.3 shows the network detection capabilities for focal depths of 0 and 10 km. The use of a focal depth of 10 km was not found to change the area covered by the 0.5 ML contour significantly and, therefore, the focal depth of 10 km was used in all subsequent network detection capability calculations.

Two rules of thumb in seismic network design were also considered:

- Ideally, epicentres should be inside the network and the azimuthal gap (the largest of all angles among the lines connecting a potential epicentre with all the stations in the network) should be less than 180°. The network geometry suggested in Figure 8.3 fulfils this rule throughout the entire study area.
- For an accurate focal depth estimate, the nearest station should be no further away than one to two times the hypocentral depth. Increasing station density in order to improve the depth accuracy, however, is not considered practical for a baseline network and it was concluded, therefore, that 12 seismic stations are sufficient to detect and locate all events with a magnitude of ≥ 0.5 ML in the NCB.

Figure 8.4 shows that, assuming earthquake recordings are made by a minimum of three stations, the network geometry example is expected to detect all events in the NCB with a magnitude ≥ 0.25 ML. However, events of ≤ 0.5 ML cannot be properly located, as this requires a minimum of six station recordings (see above).

Under favourable conditions (less noise), the example network geometry can provide good location and magnitude accuracy throughout the NCB for all events with a magnitude ≥ 0 ML. For more sophisticated studies that require detection by more than 10 stations, the detection threshold of the network increases for the NCB to approximately 0.8 ML (see Figure 8.4b).

The impact of changes to station location was then evaluated. Changes in station locations of ± 2 km were found to have only a small impact on network capability.

The narrow Loop Head peninsula in the CB has a strong influence on the network design for that area, as ideally, seismic stations should be located at least

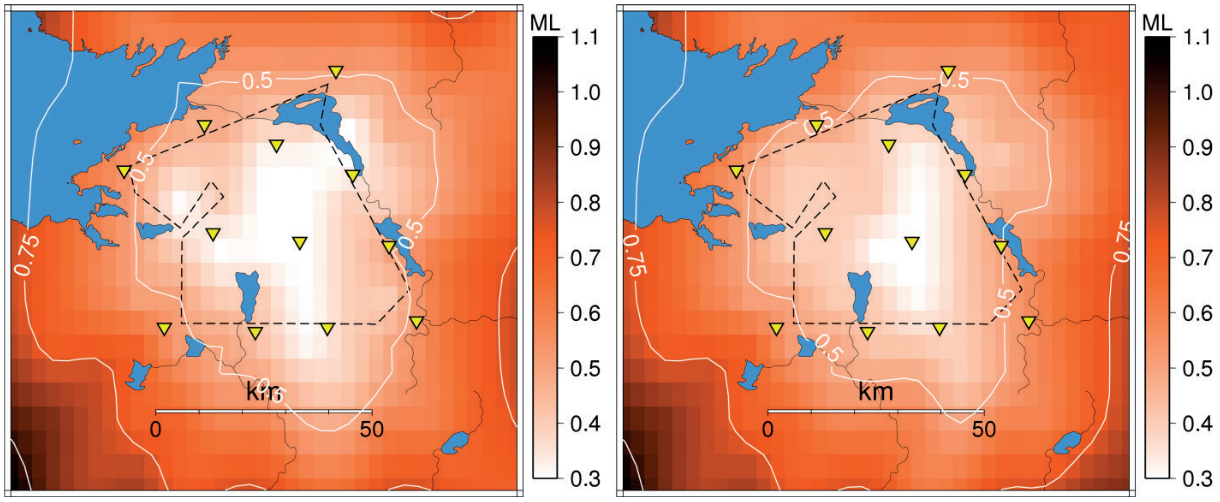

Figure 8.3. Capability plot of the example network for the NCB for (a) a focal depth of 0 km and (b) a focal depth of 10 km.

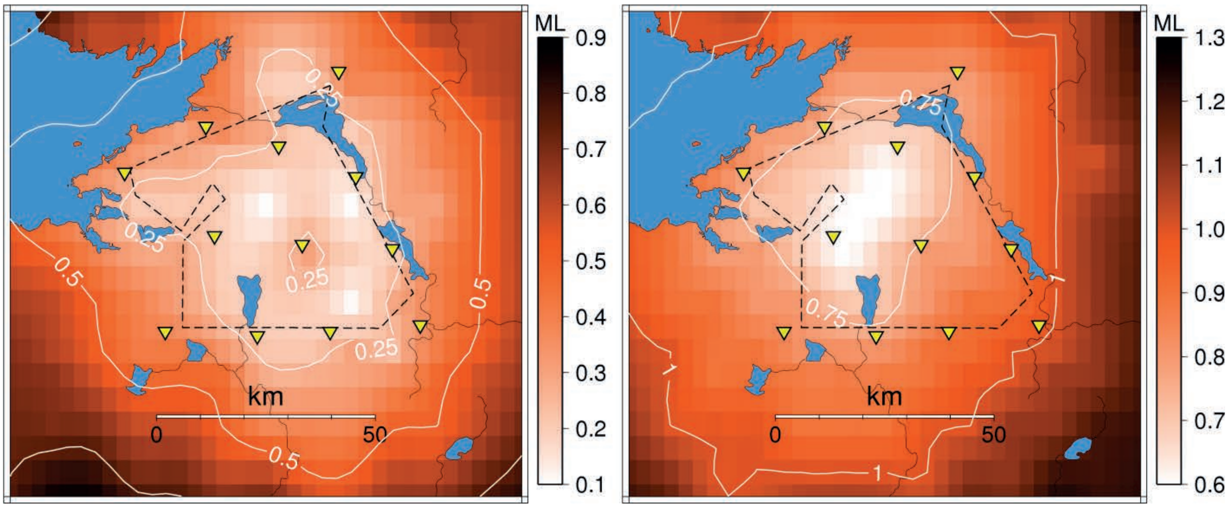

Figure 8.4. Capability plots of the example network for the NCB assuming (a) earthquake recordings by at least three stations and (b) earthquake recordings by at least 12 stations.

4 km from coastlines directly open to the Atlantic Ocean due to high noise levels. It was found that determining the location and magnitude of all local earthquakes with magnitudes ≥0.5 ML would require 10 stations in the CB (Figure 8.5a and b).

Based on the calculated example of network geometries and the required station location accuracy, example deployment target zones with a radius of 2 km (to allow for issues such as noise sources, ground conditions and land usage) for each seismometer location are presented (see Figure 8.6 and Figure 8.7). It should be noted that the calculated network configurations are just examples and were designed in order to estimate the required number of seismic stations in each of the two baseline networks. Many other configurations would also satisfy the basic requirements described above. If the presented configurations were used for an actual network deployment, flexibility to make significant adjustments to station target zones might be required and the capability of the changed network geometry would have to be reassessed.

8.6 Instrumentation Specifications

It is important to identify the seismic frequency range of interest when considering instrumentation specifications. The technical specifications of the seismic sensors and recorders should allow for the generation of high-quality earthquake catalogues for the two study areas, which include locations and accurate magnitude

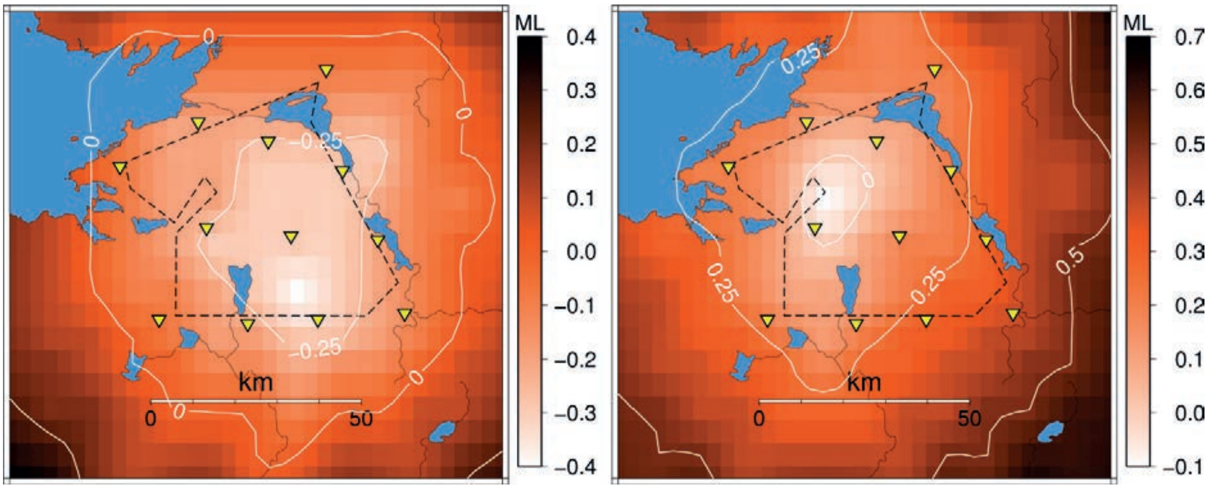

Figure 8.5. Capability plots of the example network for the CB assuming (a) earthquake recordings by at least six stations and station noise levels of 1–2 nm and (b) earthquake recordings by at least six stations and station noise levels of 0.2–0.5 nm.

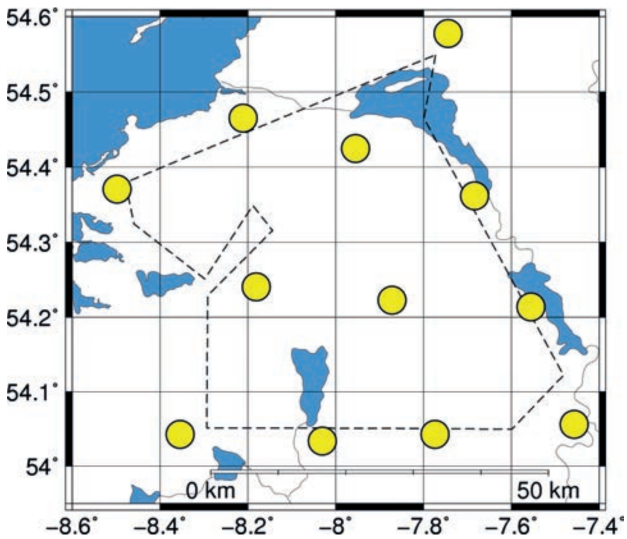

Figure 8.6. Example deployment target zones for the NCB.

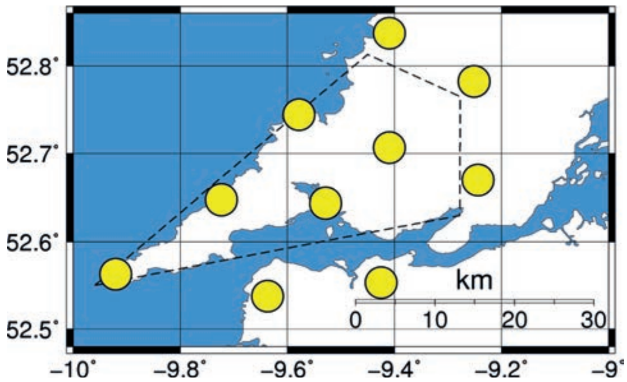

Figure 8.7. Example deployment target zones for the CB.

estimations in the range –0.5 to 4 ML. While equipment with a very high dynamic range is suggested for production monitoring installations close to UGEE operations, standard high-quality broadband sensors with a dynamic range of at least 140 dB at 1 Hz are considered adequate for the baseline study; this is discussed in more detail in *Summary Report 2: Baseline Characterisation of Seismicity*. The seismometers should be installed directly on bedrock to minimise the effect of seismic noise. Sites on stiff overburden should be chosen if bedrock sites cannot be realised. Borehole seismometer installations are not recommended for the baseline study. However, in the complete absence of bedrock or stiff soil over a significant part of the area of interest, some shallow borehole sensors may be required.

9 Examination of Global Experience of Seismic Events Stimulated by UGEE Operations (Task 8)

9.1 Introduction

This task reviewed induced seismicity in UGEE operations worldwide, as well as seismicity related to other comparable industrial operations. Measures for mitigating the risk of induced earthquakes in energy technologies were reviewed and a number of recommendations were made specifically for UGEE operations in Ireland; this is fully detailed in *Summary Report 2: Baseline Characterisation of Seismicity*.

9.2 Seismicity Induced by Hydraulic Fracturing in UGEE Operations

The general consensus is that the process of hydraulic fracturing a well, as presently implemented for shale gas recovery, does not pose a high risk for inducing either felt, damaging or destructive earthquakes. However, most sites of UGEE operations lack independent instrumentation for monitoring induced seismicity; therefore, earthquakes with magnitudes of 2.5 or less are unlikely to be felt or even detected unless local seismic monitoring networks are in place.

Over the past few decades, observations from over 35,000 hydraulically fractured shale gas wells in the USA suggest that the magnitudes of the seismic events induced by these fracture treatments are generally very small. Magnitudes of the induced microseismicity recorded during monitored hydraulic fracture stages in the Barnett Shale, Texas, typically lie in the range of –3.0 to 1.0 Mw, which means they are unlikely to be felt or even recorded unless a specific monitoring network is in place. However, it should be noted that most sites of UGEE 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.

There are at least five documented examples of earthquakes with magnitudes greater than two that have been conclusively linked to hydraulic fracturing for shale gas exploration/recovery:

- Blackpool, UK, in 2011, with a magnitude 2.3 ML earthquake.
- Garvin County, south-central Oklahoma, in 2011, where the largest earthquake had a magnitude of 2.9 ML.
- Horn River, Canada, in 2011, with a largest magnitude of 3.8 ML.
- Montney Trend, Canada, from May 2013 to October 2014 where 15 earthquakes had magnitudes of 3.0 ML or greater. To date, this is the largest known earthquake triggered by hydraulic fracture operations in a hydrocarbon field anywhere in the world.
- Crooked Lake, Alberta, Canada, in 2013–2104 where 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-north-west of Fox Creek, is also suspected to be a result of hydraulic fracturing.

It is likely that an earthquake similar in magnitude to the largest that occurred in Horn River, Canada, would be strongly felt and could even cause some superficial damage. In addition, if an earthquake of such a magnitude were to occur in Ireland where felt seismicity is very rare, it would be likely to cause rather more concern among the local population than it would in other parts of the world where earthquakes of this magnitude are more frequent. However, the maximum magnitudes 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.

In Lancashire, UK, 58 earthquakes were linked to fluid injection during hydraulic fracturing at the Preese Hall well in 2011. The largest had a magnitude of 2.3 ML and was felt locally. These hydraulic fracture treatments were carried out during exploration of a shale gas reservoir in the Bowland basin, Lancashire. As a result of the earthquakes, operations were suspended at Preese Hall.

Despite these examples of earthquakes induced by hydraulic fracturing, the process appears to pose a low risk of inducing destructive earthquakes. A report by the US National Research Council in 2012 (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. 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.

9.3 Seismicity Induced by Wastewater Disposal

In contrast to hydraulic fracturing, the subsequent disposal of the wastewater from hydraulic fracturing operations by injection can lead to significantly larger earthquakes and there is a significant body of evidence suggesting that wastewater disposal by injection to deep wells poses a significant seismic risk.

There are numerous examples of earthquakes induced by disposal of waste fluids from the hydrocarbon industry in deep injection wells. This has led to a dramatic increase in the number of earthquakes in the central and eastern USA. in the last few years. In addition, several of the largest earthquakes in the US midcontinent in 2011 and 2012 may have been triggered by nearby disposal wells. For example: a 4.0 Mw earthquake on 31 December 2011 in Youngstown, Ohio (Kim, 2013); a magnitude 4.7 earthquake in central Arkansas in 2011 (Horton, 2012); and a magnitude 5.7 earthquake in Prague, central Oklahoma (Kerenan *et al.*, 2013).

The report by the US National Research Council (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.

The recent increases in earthquake activity in many areas of the central and eastern USA that have been linked to wastewater injection for deep disposal provide a considerable body of evidence that this activity has a non-negligible contribution to the seismic hazard. If wastewater disposal on a similar scale were to proceed in Ireland, then increases in seismic activity may also be observed; however, background earthquake activity in Ireland is lower than in the central and eastern USA, so the probability of earthquakes with similar magnitudes should be lower and will depend on the state of stress in existing faults.

It should be noted that, although many wastewater injection wells can be associated with earthquakes, the majority are not. Additionally, while some of the wastewater comes from hydraulic fracturing, many wastewater injection wells are used to dispose of water from conventional hydrocarbon production.

9.4 Controlling Factors

In general, the seismicity induced by hydraulic fracturing depends on the strength of rocks in the geological formations of interest, the size and state of stress of any faults in the area and the pressure change induced by the hydraulic fracture process, which is affected by the volume of injected fluid and the rate of injection.

9.5 Mitigation

Extensive experience of induced seismicity in enhanced geothermal systems has led to a series of measures to address induced seismicity that may be considered as industry best practice. For example, the US Department of Energy *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems* (Majer *et al*., 2012) lists seven steps for mitigating seismic risk (Table 9.1).

Traffic light systems linked to real-time monitoring of seismic activity have also been developed, which are essentially control systems for management of induced seismicity.

Given that the UGEE process appears to pose a low risk of inducing destructive earthquakes, there are relatively few published measures for mitigation of seismic risk. However, both the British Columbia Oil and Gas Commission and the UK Department of Energy and Climate Change set out a number of recommendations. The latter are part of the regulatory roadmap for future hydraulic fracturing operations in shale gas exploration and production in the UK. These recommendations are summarised in Table 9.2.

Table 9.1. Seven steps for mitigating seismic risk from the US Department of Energy; steps are listed in the order to be followed (Majer *et al.*, 2012)

Step 1	Perform a preliminary screening evaluation
Step 2	Implement an outreach and communication programme
Step 3	Review and select criteria for ground vibration and noise
Step 4	Establish seismic monitoring
Step 5	Quantify the hazard from natural and induced seismic events
Step 6	Characterise the risk of induced seismic events
Step 7	Develop risk-based mitigation plan

Table 9.2. Recommendations for future hydraulic fracturing operations in the UK (from Green *et al.*, 2012)

1	Use all available geological information to assess the location of faults before wells are drilled to avoid hydraulically fracturing near faults
2	Use British Geological Survey records to assess baseline levels for seismic activity
3	Inject as little fluid as necessary into the rock during fracturing
4	Monitor seismic activity during and after fracturing
5	Use a traffic light system that controls whether or not injection can proceed, based on that seismic activity

From both these studies, it is 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 active faults in any potential UGEE exploration or production sites may require a more accurate model of the sub-surface geology than is presently available in some areas. Secondly, seismic monitoring should be used both to establish reliable baselines for background activity and as an essential part of a traffic light system.

In all the published examples of seismicity associated with hydraulic fracturing in the hydrocarbon industry, only the five examples presented earlier have led to felt seismicity that could cause some alarm to local residents. However, such an earthquake would be unlikely to cause structural damage. There are examples of mining-induced earthquakes with magnitudes of 3.0 ML in the UK that reportedly caused superficial damage, however, there have been no reports of structural damage from mining-induced earthquakes in the UK in the past 40 years.

9.6 Discussion

Knowledge of fault systems in the sub-surface is generally limited to areas where detailed geophysical surveys have been carried out. It is clear that high-resolution monitoring of background seismicity in Ireland is required prior to commencement of any UGEE operations so that the low seismic activity rates suggested by existing instrumental monitoring data and historical data can be confirmed, and also so that any unusual seismicity can be identified. Low activity rates suggest that it should not be difficult to identify earthquakes related to UGEE operations. However, seismological methods alone cannot discriminate between man-made and natural tectonic earthquakes.

In addition, the pre-existing state of stress and pore pressure acting on a fault are also usually unknown. Therefore, although effective-stress models provide a basis for modelling induced earthquakes, the initial conditions to constrain this model are generally lacking. We also often lack knowledge about the hydrological properties of the sub-surface. This limits the use of geomechanical modelling methods. Measuring the initial stress state and pore pressure, tracking the injection history and careful seismic monitoring may help to improve understanding.

A traffic light system linked to real-time monitoring of seismic activity is an essential mitigation strategy that would also need to accompany any UGEE operations in Ireland. This requires the definition of acceptable thresholds for the cessation and recommencement of operations. Published recommendations for these thresholds in UGEE operations differ widely; however, it seems clear that any thresholds should be based on levels of ground motion that may represent a hazard or a public nuisance. Existing regulatory guidelines for ground vibrations caused by blasting could also provide a useful framework for this purpose. The British Standards BS 6472-2 and BS 7385-2 define limits for ground vibrations caused by blasting that are acceptable for human exposure and above which cosmetic damage could take place. The equivalent German DIN4150-Part 3 (Effects of Vibration on Structure) also examines levels of vibration at which building damage may occur.

Cosmetic damage may only be likely for earthquakes with magnitudes of 3 or above within a few kilometres of the hypocentre. However, ground motions from earthquakes typically show large aleatory variability and, in the face of this uncertainty, it would seem prudent to make conservative decisions on any thresholds. These results suggest that an upper magnitude threshold for the cessation of operations in the range 2–2.5 may be practical. Direct use of a ground motion threshold, such as peak ground velocity, may be preferable to magnitude threshold, since this avoids the issue of magnitude calculation and the averaging of a number of ground motion values.

A growing body of evidence of changes in observed seismicity rates and significant earthquakes linked to deep water injection (DWI) of wastewater from the hydrocarbon industry suggests that this activity may pose a rather greater seismic risk. Reports from Project B (*Final and Summary Reports 4: Impacts and Mitigation Measures*) of this programme discuss the possibility that DWI could be one of several potential ways of dealing with wastewater. However, currently, the practice is not legal under EU law, as explained in the final report for Project C (*Final Report 5: Regulatory Framework for Environmental Protection*).

9.7 Conclusions

The general consensus among most authors is that the process of hydraulic fracturing a well, as presently implemented for shale gas recovery, does not pose a high risk for inducing either felt, damaging or destructive earthquakes. However, there are also well-documented examples of earthquakes with magnitudes greater than 2.0 that have been conclusively linked to hydraulic fracturing for shale gas exploration/recovery. It is likely that an earthquake similar in magnitude to the largest that occurred in Horn River, Canada, could be strongly felt and could even cause some superficial damage. In addition, if an earthquake of such a magnitude were to occur in Ireland, where felt seismicity is very rare, it would be likely to cause rather more concern among the local population than it would in other parts of the world where earthquakes of this magnitude are more frequent. However, the maximum magnitudes 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.

The following recommendations were made:

1. The seven steps for mitigating seismic risk identified in the US Department of Energy *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems* (Majer *et al*., 2012) listed in Table 9.1 should be followed.
2. A traffic light system linked to real-time monitoring of seismic activity is an essential mitigation strategy that will also need to accompany any UGEE operations in Ireland. Thresholds for the cessation and recommencement of operations should be based on levels of ground motion that may represent a hazard or a public nuisance. An upper magnitude threshold for the cessation of operations in the range 2–2.5 may be practical.
3. Direct use of a ground motion threshold, such as peak ground velocity, may be a suitable alternative to using earthquake magnitude. This would allow thresholds to be directly linked to existing guidelines for ground vibrations caused by blasting such as the British Standards BS 6472-2 and BS 7385-2, and the equivalent German DIN4150-Part 3
4. Any possibly active faults in the area of interest using all available geological and geophysical data should be characterised.
5. Full knowledge of existing active fault zones at the site should be established and considered prior to any deep injection of flowback or produced water.

10 Assessment of Pre-fracturing Modelling Techniques (Task 9)

10.1 Introduction

The physical properties of rocks control the propagation of fractures and realistic modelling of these properties is a prerequisite for accurate forecasting of distributions of fracture length and orientation. It is now accepted that several of the parameters are invariant to changes in scale from a few millimetres to many kilometres.

This raises several issues for the forecasting of fracture populations in the hydraulic fracturing environment and means that only through the understanding of the physical state of the rock mass and how it is responding to a particular set of forcing conditions can a useful estimate be made of how the fracture set is developing and how this might continue to develop through the injection. Exponential divergence of initially similar initial conditions means that measurements must be made and updated continuously in order to understand and forecast the fracture propagation.

Typically, models assume a simple shape for the fracture that allows the modeller to solve the appropriate equations for a specific medium with an assumed homogeneous set of physical properties for fracture growth. So-called mineback experiments, where rock, previously fractured by fluid injection, was excavated to reveal the fractures induced, show that these simple geometries bear no resemblance to the fractures observed in these experiments.

Fortunately, modern seismological and geodetic instrumentation and analytical techniques for the near-real-time monitoring of seismicity and deformation offer the real possibility of empirically tracking and forecasting the development of fractures before and during any potential fracking operation. While published results from mineback experiments, laboratory rock mechanics experiments and field tiltmeter deployments are unlikely to assist in forecasting likely fracture lengths, published microseismic data may provide a workable guide. However, published estimates make unreasonable assumptions about the likely maximum event size that would, in turn, lead to a significant underestimate of the maximum vertical length of fractures in previous fracking treatments. A general framework was developed in Task 9 to provide a more robust forecast of the possible vertical height of fractures by modelling of the formation of fractures from widely accepted seismological scaling relations.

10.2 Observational Estimates of Fracture Length

There is a wealth of literature on the vertical propagation of fractures resulting from the injection of high-pressure fluid into low-permeability rocks. It is the view of the authors that none of this literature provides compelling evidence on which general statements can be made about likely fracture lengths or the possibility of contamination of aquifers in the Irish context. While many of these publications are selective in their choice of data and make assumptions that are contradictory to more objective observations, some published data do provide a reasonable basis on which to place a lower limit on the possible fracture heights that might result from UGEE operations.

10.3 Direct Observations of Fractures

Direct observations of fractures can be made by mineback experiments, in which previously fracked rocks are excavated to expose the fractures generated. The objective of this work is to improve hydraulic fracture technology rather than to estimate the maximum fracture height and, consequently, such studies never completely sample the fracture field and therefore the maximum fracture height cannot be observed. The technique is explicitly biased towards providing evidence for fracture termination rather than propagation.

Laboratory testing is frequently used to explore the fractures generated by the differential stressing of rocks by various mechanisms. No literature was found describing laboratory experiments that have been carried out to explore the maximum fracture height induced in laboratory samples.

10.4 Indirect Observations of Fracturing

The two main methods for the indirect observation of fracturing are the use of tiltmeters to observe deformation and the use of microseismic observations. The former is integrative and provides evidence of the bulk properties of the fracture field, whereas the latter, arguably, provides information about the formation of individual fractures.

Tiltmeters very accurately measure the slope of a surface. Surface arrays record changes in surface slope due to deformation of the ground by the production of fractures and it is argued that they are sensitive to the orientation of the generated fractures. Downhole tiltmeter arrays record the internal deformation of the rock volume; these are much more sensitive than surface arrays to the fractures being observed, but less sensitive to fracture orientation. While they might usefully help to model the permeability at depth, which is of most interest to oil industry, they are an inappropriate technology for elucidating maximum fracture height.

Published tiltmeter data demonstrate that, contrary to industry claims, vertical rather than horizontal fractures are dominant at all depths. Fractures at shallow depths might therefore interact with aquifers if the separation between the fractured rocks and the base of the aquifer is inadequate.

The generation of fractures progresses by the sequential brittle fracturing of rock. Each brittle failure generates seismic waves in the rock volume that can be detected using seismometers deployed either in surface or in downhole arrays. Taken in the whole, the data produces an image of the entire fractured volume.

An assessment of the maximum possible fracture height must involve two separate lines of evidence:

1. the maximum likely vertical extent of the microseismicity;
2. the length of the longest fracture associated with the seismicity, which should be assumed to be vertical.

Several studies have reviewed data from many thousands of treatments across the major tight gas formations in North America. In general, there is little, if any, systematic relationship between vertical extent of seismicity with depth of the perforation. The separation between the wells and the seismicity in all the cases reviewed is large, so, assuming no pre-existing through-going fractures or faults, it is unlikely that any contamination has occurred from the data that are publicly available. This is site-dependent and no general case can be made for the safety of operations on the basis of these data.

Maxwell (2011) systematically examined the published data on the vertical extent of fracking-induced microseismicity; analysis of these data suggests that only one in 20 projects in North America produced recorded seismicity that was 300 m (or more) shallower than the perforation. This does not show that the maximum upwards fracture extent is 300 m above the perforation. An additional component that relates to the finite extent of the fractures associated with each event must also be included. It is considered that the probable maximum magnitude does not vary with depth.

10.5 Fracture Length Distribution Due to Seismicity

Having developed estimates of the likely vertical extent of microseismic activity, an estimate of the likely size of fractures that are formed during this seismicity is required. Estimates that fractures associated with the largest events are of the order of 10 m long are not supported by the worst-case data or experience. A more realistic worse-case estimate was therefore developed.

The aim was to use scaling relations between event magnitude and fracture length to forecast the distribution of hydraulic fracture dimensions from a known magnitude distribution. Since we are dealing with newly generated fractures, the problem is approached from the perspective of fracture mechanics and not fault friction.

It is suggested that scaling relations between magnitude and rupture dimensions of tectonic earthquakes are applicable. In order to estimate the distribution of fracture lengths, an estimate of the distribution of event magnitudes for the fracked events is required. The appropriate model for the frequency-magnitude scaling of fracked events is still under discussion. However, it is important to point out that seismicity rates are likely to vary with time, not only depending on the injection itself, but also on the diffusion of fluid through an unknown permeability field. Operational monitoring and real-time re-estimation of local seismicity rates and frequency magnitude scaling is therefore essential and is assumed in what follows. In addition, it is reiterated that the work in this task does not relate to the seismic hazard, which comes almost completely from "triggered" seismicity and not "fracked" seismicity; different rates and magnitude distributions apply for the seismic hazard problem.

For a typical catalogue from a hydraulic fracturing project (with very small numbers of larger magnitude events), the distribution is very poorly sampled and the magnitude distribution does not reflect the (potentially large) variability in the rupture dimensions at a given magnitude.

The approach adopted was to estimate the distribution of fracture lengths by Monte Carlo methods; a large number of synthetic fracked catalogues of events with moment magnitudes (large enough that the distributions are well sampled and the distributions at large magnitudes have converged) were generated and fracture lengths assigned to these events. The mean properties of all the Monte Carlo simulations were used to determine the distribution function for fracture length for the hydraulic fracturing scenario. The simulations reflect typical rates of fracturing that might be expected, based on a few hours of injection.

While the individual synthetic catalogue shows a lot of scatter, particularly at larger magnitudes (those in which we are interested in), the mean values for all the samples converge to the model values; the distribution is well sampled by 10,000 Monte Carlo simulations. It was found that the probability of large events rapidly becomes very small.

Individual fracture lengths cannot be forecasted, since they depend on unknowns such as local heterogeneity or anisotropy in the material properties. The method developed allows for the accounting of uncertainties due to this unknown variability in the rupture lengths of events of a given magnitude.

Many thousands of treatments in North America indicate that the frequency magnitude distribution rolls off at around magnitude 1. Making this assumption, the probability for increasing fracture length t falls off rapidly, approaching zero above crack dimension $L = 5$ m (close to zero, since the Monte Carlo sampling has not resolved probabilities for extremely rare, very large fractures, so in this case Lmax for any given stimulation would be of the order of 10 m).

It was concluded that there is a well-defined upper limit for the fracture length, because there is a roll-off in the frequency magnitude distribution. However, it is clear that larger events associated with hydraulic fracturing are occasionally recorded. It would therefore seem prudent to consider fractures that might be associated with such events. In the case of events up to magnitude 3, and following a similar logic, we might well expect a roll-off at around 200 m but with rare fractures occasionally exceeding this length.

10.6 Discussion

Since forecasts depend on detailed local knowledge of the relevant geology and underlying seismicity rates, much of which will not be available on the short term, this study has been able to go only as far as developing the protocol for a forecast. These results do not, therefore, constitute a forecast for fracture lengths from hydraulic fracturing in Ireland.

This report deals only with fracked earthquakes and not with triggered events, and so does not relate to the seismicity hazard from fracking. There is no evidence in the published literature that triggered seismicity has a definable maximum magnitude at any scale relevant to hydraulic fracturing projects.

The nature of the frequency magnitude distribution at the upper magnitude limits is not well understood. There are physical reasons to suggest there should be an upper magnitude for fracked seismicity. However, in practice, it is very difficult to robustly demonstrate from the data that this is a good model for the magnitudes of real events, partly because of the difficulties in separating triggered from fracked earthquakes.

It has been assumed throughout that some parameter values will come from real-time operational monitoring of the fracked seismicity (with possible initial estimates from the baseline).

10.7 Conclusions and Recommendations

The literature review shows that microseismic observations are likely to provide a reasonable guide to the distribution of fracturing activity surrounding any particular well. Estimates of likely fracture heights can be made by the addition of the likely length of fractures associated with these microseismic events.

A protocol was developed to forecast the distribution of hydraulic fracture dimensions from a known magnitude distribution using empirically determined scaling relations between earthquake magnitude and rupture length. The parameters used for the stochastic model should be replaced by values determined initially from the baseline survey and then updated in near-real-time during any fracking operation.

Data from tiltmeters provide clear evidence that vertical fractures can propagate into shallow depths where they might interact with aquifers if the fracking is sufficiently shallow.

Inspection of the vertical extent of microseismic activation shows that the vertical extent of fracturing is likely to be insensitive to frack depth.

Data show that the distribution of distance of microseismic events from the perforation is skewed to shallow depths, although they support the conclusion that 95% of North American projects had worst-case events less than 300 m above the perforation.

Variability in microseismic magnitude appears to be controlled by sub-horizontal layering and is largely insensitive to frack depth.

There is no well-defined maximum magnitude for all seismicity induced by fracking.

If, as is suggested for fracked (not triggered) seismicity that is responsible for increased vertical permeability, there is a roll-off in the frequency magnitude distribution, a well-defined upper magnitude limit exists. However, for any particular project there will be an uncertainty in the maximum observed magnitude.

In addition to the uncertainties from poor sampling of the larger magnitude events, rupture lengths also have large uncertainties that reflect mainly unknown variability in the material properties.

Fracture lengths show a strong decrease in probability, suggesting that there is a well-defined (although "soft") upper limit on the fracture length at a site. However, there is a relatively long tail on the distribution, suggesting that these large events are very rare. Published data on fracked events resulting from thousands of treatments in the USA suggest that $M^* = 1.0$ might be a realistic model for fracked seismicity. In this case, the worst-case fractures would be of the order of 10 m that implies a worst-case vertical fracture extent of approximately 300 m above the perforation.

Results suggest that for $M^* = 3$ (which would be consistent with worst-case events in other areas), fracture lengths of up to several hundred metres could imply a worst-case vertical extent of approximately 500 m above the perforation.

The expected value for the longest fracture would become more certain shortly after the commencement of fracking, could be updated in near-real-time thereafter and could be included in any proposed traffic light system governing the extraction.

The top of a lithological unit, such as the top of the shale, would be expected to provide a significant, though not impenetrable, barrier to upwards fracture propagation, particularly at shallow depths. This moderates the threat of extreme fractures propagating to an aquifer far above the shale top.

Given the unpredictability both of the location and magnitude of the worst microseismic event (in the sense that it produces the shallowest fracture) and the associated uncertainty in the length of the fracture it generates, the expected worst-case vertical extent of fracturing is very uncertain.

On the basis of this study, and considering the joint probability of a large event occurring at a great distance from the perforation, we conclude that we would have a realistic expectation ($P \approx 0.05$) of fractures approaching 300 m and fractures extending more than 500 m above the perforation could occur in extremely rare cases.

The arguments advanced in this study assume that the formation to be fracked does not contain permeable faults that connect with an overlaying aquifer. During fracking, the permeability of the entre volume would be increased connecting any permeable thoroughgoing fault to the fracked volume and thereby potentially connecting the fracked volume to the surface.

11 Conclusions

Unconventional gas exploration and extraction involves hydraulic fracturing (fracking) of low-permeability rock to permit the extraction of natural gas on a commercial scale from unconventional sources, such as shale gas deposits, coal seams and tight sandstone. The main aim of the UGEE JRP is to further the understanding of potential impacts on the environment and human health from UGEE projects/operations.

Project A2 of the JRP dealt with the baseline characterisation of seismicity, which is required for potential impacts to be assessed, and involved seven tasks.

11.1 Task 1: Assessment of Existing Baseline Monitoring Operated Worldwide for UGEE Projects/Operations

Existing experience in UGEE projects suggests that baseline monitoring before, during and after operations should be a basic key requirement of any future exploration and extraction, enabling background levels of seismicity to be reliably characterised and any unusual seismicity or active faults that could potentially be affected by operations identified.

Since seismicity rates in the island of Ireland are very low, it may require many decades of baseline monitoring to reliably determine the rates in each of the two study areas. However, it is important to test the assumption that seismicity rates are uniform across Ireland and detailed monitoring will be required to detect any unusual seismicity that may suggest that seismicity rates are higher in the study areas, or that there is seismicity associated with any specific fault structure. A monitoring period of 1–2 years may be appropriate for this purpose.

The reliable and uniform detection of seismic events across a given area of interest requires a uniform distribution of monitoring stations. The density of the stations, along with the noise levels at each station, control the lowest magnitudes that can be reliably detected. Higher station densities will be required to detect and locate lower magnitudes. Reliable location and magnitude measurement places additional constraints on network design, since measurements at more stations are needed than for detection alone.

Extensive experience of seismic monitoring in the geothermal industry may be considered as best practice for UGEE monitoring, along with appropriate control measures for the mitigation of risks associated with induced earthquakes.

The case studies discussed in this report highlight 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.

11.2 Task 2: Evaluation of Methodologies for the Monitoring of Ground Deformation That May Be Associated with UGEE Projects/Operations

The assessment concluded that the InSAR technique for ground motion monitoring is valid for the island of Ireland, and for the CB and NCB study sites in particular.

Ground deformation from UGEE projects/operations will not necessarily result in damage to structures but it is important to invest in the necessary instrumentation to quantitatively monitor the motion at the surface in order to gauge potential damage to structures, and to address the potential concerns of the public and policymakers regarding impacts on the environment.

Ongoing monitoring using InSAR techniques will be facilitated by a recently launched ESA satellite and a sufficient volume of data was available for an InSAR analysis of Ireland by the end of 2015.

More than 99.9% of the Irish landmass is visible to the SAR satellites in at least one acquisition mode. Over 90% of the island of Ireland consists of predominantly rural land cover types and would therefore have relatively low numbers of persistent scatters that are essential for data interpretation. New analysis techniques, such as ISBAS, are showing very positive results in non-urban environments, increasing the number and density of scatterers. The increase offers significant advantages for the interpretation of ground motion, which makes it easier to relate the results to other datasets and therefore increases understanding of the ground motion.

It was concluded that any UGEE projects operating in Ireland should be monitored using historical and current satellite radar data, processed to provide InSAR results with a technique such as ISBAS. The historical data will provide a baseline of surface millimetric motions back to 1992, confirming the stability or otherwise of the surface prior to UGEE operations.

In combination with the InSAR technique, complementary *in situ* methods, such as GNSS and tiltmeters, could be deployed. A network of GNSS stations would provide data on regional surface motion from the time the instruments are installed; tiltmeters would provide complementary data on local microdeformation and fracture propagation (if installed on the surface and downhole).

11.3 Task 3: Assessment of Existing Data on Natural Seismicity in the Island of Ireland

A review of published data confirmed that earthquake activity in Ireland is very low. Historical accounts of seismic events felt in Ireland amount to only 26 events in the interval 1500–1970. Instrumental data confirm these low rates of seismic activity. Almost all the instrumental seismicity records are in areas where historical earthquakes have occurred. The exception to this is the magnitude 4.0 ML earthquake off the coast of Mayo in 2012, which is the largest Irish event in the catalogue.

Calculated earthquake activity rates for Ireland were found to vary depending on the assumed level of completeness of the earthquake catalogue. Using the same catalogue completeness thresholds as for Britain suggests that there should be an earthquake with a magnitude of 4 Mw or greater, somewhere in Ireland and the surrounding offshore area approximately every 476 years. This is in reasonable agreement with the observed data. However, more conservative estimate of catalogue completeness leads to a higher activity rate, which would lead to significantly more earthquakes than observed. This highlights the problem of estimating reliable rates in low-seismicity regions that allow seismic hazard to be reliably quantified.

The average activity rate for Britain suggests that there should be an earthquake with a magnitude of 4 Mw or greater approximately every 6 years. The reasons for the dramatic difference remain poorly understood, given the geological and tectonic similarity between Ireland and Britain.

Modelled ground motions for earthquakes with moderate magnitudes that may occasionally occur in or around Ireland suggest that ground velocities are unlikely to exceed typical levels at which cosmetic damage might occur, except close to the earthquake source.

11.4 Task 4: Assessment of the Magnitude and Physical Effects of Induced Seismicity That May Be Associated with UGEE Projects/ Operations in the Island of Ireland

A rigorous statistical forecast model was developed, based on state-of-the-art understanding of the triggering of induced seismicity. Since current catalogues are completely inadequate for forecast modelling on these spatial scales, synthetic catalogues were used to represent hypothetical baseline scenarios to allow the illustration of the nature of the uncertainties that might be expected, rather than to make specific forecasts for an injection. The uncertainties presented mean that robust estimates for basic hazard parameters are likely to be high in an area of very low seismicity; this will be the case even for the best realistic baseline.

The use of a homogeneous reference catalogue generates systematic errors in the parameter estimates. This problem can be minimised (but not solved) by a high-quality baseline deployment and data analysis to generate the best reference model possible. However, ultimately, detailed subsurface structural information will be required to understand this problem completely. The choice of fault network model has a first-order effect on the success of the seismicity forecasts. Important information on the active structure could be obtained from detailed structural studies and from any available high-quality focal mechanisms of well-recorded earthquakes in the area.

The model does not include uncertainties in earthquake locations and magnitudes or, for example, uncertainties in any of the parameters of the CRS model, such as the fault frictional constants. The uncertainties presented here can therefore be considered as the lower limits on the uncertainties that can be expected from real seismic catalogues. While these errors are considered to be relatively minor compared with the issues discussed in this report, every effort to minimise them should be made from the best seismological and structural data.

The data requirements for high-quality forecasts are significant and the specifications of baseline networks are subject to external considerations; it is expected that some progress can be made with 2 years of monitoring data. Robust forecasts of the hazard-relevant parameters of induced earthquake catalogues can only be made using a high-quality network and current best practice in data analysis.

The low background rates of seismicity observed in current Irish catalogues have two contrasting implications: from a scientific perspective the data are unlikely to allow robust forecasts of the main parameters and in terms of impacts it means that any hydraulic fracturing projects in Ireland are extremely unlikely to have any potentially troublesome seismic consequences. However, this conclusion will require confirmation by examination of high-quality baseline catalogues.

11.5 Task 5: Technical Specification for Sub-regional Seismic Baseline Monitoring

The study evaluated the detection thresholds of existing seismic networks in Ireland to assess if they are sufficient to detect and locate all local earthquakes with magnitudes ≥ 0.5 ML in the NCB and the CB.

It was concluded that the existing INSN and the UCD Wave-Obs network are not sufficient to detect and locate all local earthquakes with magnitudes ≥ 0.5 ML in the two study areas.

Local networks with an interstation spacing of between 15 and 25 km are required to reliably locate all such events during a baseline study, which should operate for at least 2 years. This would require the deployment of at least 12 seismometers in the NCB and 10 seismometers in the CB.

Example network geometries were designed to allow the detection and location of all events with magnitudes ≥ 0.5 ML during periods of elevated seismic background noise conditions, for example during stormy weather. The network capability is expected to yield a threshold between –0.25 ML and 0 ML during periods of average seismic noise levels.

Unless an event occurs within a distance of less than two focal depths from a station, reliable focal depth estimations are expected only for events with depths of more than 10 km. Improving the depth accuracy by increasing network station density is not practical for a baseline network. Such an effort would also be hampered by the lack of high-resolution seismic velocity models for the two study areas.

The network should comprise high-quality three-component broadband seismometers and their installations should comply with international best practice. Borehole seismometer installations were not recommended for the baseline study.

However, in the complete absence of bedrock or stiff soil over a significant part of the area of interest, some shallow borehole sensors may be required. The seismometers should be installed directly on bedrock to minimise the effect of seismic noise. Sites in stiff overburden should be chosen if bedrock sites cannot be realised.

It was recommended that the network should be deployed and operated by a commercial entity, but that the monitoring data should be integrated with the National Data Centre (NDC), which is operated as part of the INSN. The resulting earthquake catalogue, together with the seismic raw data, should be made publicly available through the NDC to ensure transparency.

11.6 Task 8: Examination of Global Experience of Seismic Events Stimulated by UGEE Operations

The process of hydraulic fracturing to increase the permeability of reservoir formations and stimulate the recovery of hydrocarbons is generally accompanied by microseismicity, usually defined as earthquakes with magnitudes of 2 or less, which are too small to be felt. Two types of induced events can be defined: “fracked” events, whose size is constrained by the energy of the injection process, and “triggered” events, whose size depends largely on the amount of stored up elastic strain energy already in the rocks. The “fracked” events are caused by the formation and growth of new cracks and fractures in a previously intact rock mass as a result of the injection of high-pressure fluids. The “triggered” events result from the presence of the high-pressure fluid and the stress perturbation caused by the fluid, which changes the effective stress on pre-existing faults, causing them to fail. These earthquakes can be “triggered” by very small stress perturbations; however, the potential for such events depends very much on the geological context and, given the low levels of background seismicity, the probability of large triggered earthquakes in Ireland can be considered to be small.

The general consensus among most authors is that the process of hydraulic fracturing a well, as presently implemented for shale gas recovery, does not pose a high risk for inducing either felt, damaging or destructive earthquakes. Experience in the USA, where many thousands of stimulations have been carried out, suggest that the magnitudes of the induced earthquakes in reservoirs such as the Barnett and Marcellus Shales are typically less than 1 Mw. However, most sites of UGEE operations lack independent instrumentation for monitoring induced seismicity; therefore, earthquakes with magnitudes of 2.5 or less will fall below the detection thresholds of regional seismic monitoring networks. Earthquakes of this size are unlikely to be felt or even detected unless local seismic monitoring networks are in place.

There are at least five documented examples of earthquakes with magnitudes greater than 2 that have been conclusively linked to hydraulic fracturing for shale gas exploration/recovery. The largest (4.4 Mw) was in Montney Trend, Canada, in 2013–2014. It is likely that an earthquake that is similar in magnitude would be strongly felt and could even cause some superficial damage. In addition, if an earthquake of such a magnitude were to occur in Ireland, where felt seismicity is very rare, it would be likely to cause rather more concern among the local population than it would in other parts of the world where earthquakes of this magnitude are more frequent,

There are large uncertainties in forecasting seismicity in areas such as Ireland, where the background activity rates are low. However, although it is difficult to quantify, the probability of significant triggered seismicity depends strongly on the prior activity in the area. As a result, significant events are very unlikely in areas such as Ireland, where the background seismicity rate is extremely low, and there is no evidence to suggest that the process of hydraulic fracturing for shale gas recovery poses a higher risk for inducing earthquakes than in other parts of the world. This risk may be further reduced by effective mitigation.

In contrast, the growing body of evidence of changes in observed seismicity rates and significant earthquakes linked to long-term disposal of wastewater by deep well injection from the hydrocarbon and other industries suggests that this activity may pose a rather greater seismic risk.

Experience of induced seismicity in enhanced geothermal systems has led to a series of measures to address induced seismicity that may be considered as industry best practice, and, as such, may be considered appropriate for mitigating the risk of induced seismicity in UGEE operations. For example, an operational traffic light system linked to real-time monitoring of seismic activity is an essential mitigation strategy that should accompany any UGEE operations in Ireland.

Other means of mitigating earthquake risk may require improved understanding of the Earth’s sub-surface in areas of unconventional hydrocarbon potential, such as improved characterisation of existing fault zones, although this may be difficult to achieve without detailed geophysical surveying. The pre-existing state of stress on a fault determines how close it is to failure, so faults that are critically stressed may require only a small stress perturbation to cause them to fail. The pressure change induced by the hydraulic fracture process is mainly controlled by the volume of injected fluid and the rate of injection, where larger volumes and higher injection rates generate higher pressures. Recent work suggests that maximum magnitude is related to the total volume of injected fluid.

There remain a number of gaps in our existing knowledge of induced seismicity. For example, the pre-existing state of stress and pore pressure acting on a fault are usually unknown. We also often lack knowledge about the hydrological properties of the sub-surface. Measuring the initial stress state and pore pressure, tracking the injection history and careful seismic monitoring may help to improve understanding.

11.7 Task 9: Assessment of Pre-fracturing Modelling Techniques

The literature on the fractures associated with unconventional hydrocarbon recovery by fracking was reviewed and it was shown that microseismic observations are likely to provide a reasonable guide to the distribution of fracturing activity surrounding any particular well.

Estimates of likely fracture heights can be made by the addition of the likely length of fractures associated with these microseismic events.

A protocol was developed to forecast the distribution of hydraulic fracture dimensions from a known magnitude distribution using empirically determined scaling relations between earthquake magnitude and rupture length. The parameters used for the stochastic model are for illustration and should be replaced by values determined initially from the baseline survey and then updated in near-real-time during any fracking operation.

Data from tiltmeters provides clear evidence that vertical fractures can propagate into shallow depths where they might interact with aquifers if there is inadequate separation. Inspection of the available data shows that the vertical extent of fracturing is likely to be insensitive to frack depth. The distribution of distance of microseismic events from the perforation is skewed to shallow depths although the data support the conclusion that 95% of North American projects had worst-case events less than 300 m above the perforation.

Variability in microseismic magnitude appears to be controlled by sub-horizontal layering and is largely insensitive to frack depth. There is no well-defined maximum magnitude for all seismicity induced by fracking. If, as is suggested for fracked (not triggered) seismicity, which is responsible for increased vertical permeability, there is a roll-off in the frequency magnitude distribution, a well-defined upper magnitude limit exists. However, this limit is, in general, “soft”, meaning that for any particular project, there will be an uncertainty in the maximum observed magnitude. In addition to the uncertainties from poor sampling of the upper magnitudes in power law distributions, the rupture lengths also have large uncertainties from the empirical relations, which reflect mainly, unknown variability in the material properties.

The modelling suggests a well-defined (although “soft”) upper limit on the fracture length. However, there is a relatively long tail on the distribution, suggesting that there are very rare large events. Based on parameters derived from data on thousands of fracked events in the USA, the worst-case fractures would be of the order of 10 m, which implies a worst-case vertical fracture extent of approximately 300 m above the perforation.

Parameters from close to worst-case events can be used to predict that fracture lengths of up to several hundred metres could be possible, implying a worst-case vertical extent of approximately 500 m above the perforation. The expected value for the longest fracture would become more certain shortly after commencement of fracking, could be updated in near real time thereafter and could be included in any proposed traffic light system governing the extraction.

The top of a lithological unit, such as the top of the shale, would be expected to provide a significant, though not impenetrable, barrier to upwards fracture propagation, particularly at shallow depths, moderating the threat of extreme fractures propagating to an aquifer far above the shale top. Given the unpredictability both of the location and magnitude of the worst microseismic event (in the sense that it produces the shallowest fracture) and the associated uncertainty in the length of the fracture it generates, the expected worst-case vertical extent of fracturing is very uncertain. On the basis of this study, and considering the joint probability of a large event occurring at a great distance from the perforation, it was concluded that there is a realistic expectation of fractures approaching 300 m above the perforation and fractures extending more than 500 m above the perforation could occur in extremely rare cases.

11.8 Data Gaps

It should be noted that seismological methods alone cannot discriminate between man-made and natural tectonic earthquakes. This strengthens the case for site-specific seismic monitoring and detailed recording of injection parameters to reduce uncertainties in earthquake locations and to compare the temporal evolution of seismic activity associated with any hydraulic fracture operations. Understanding of the hazard from induced earthquakes for a specific site would benefit from the following additional data:

- improved 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; this will require improved monitoring and observation;
- 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; this would be expected to be part of the operator’s exploration activities;

- industrial data from proposed hydraulic fracturing operations such as injection rates, volumes and downhole pressures; this would also be expected to be part of the operator's exploration activities.

Operational monitoring arrays could be implemented independently, but the data should be openly available to maintain public confidence and form part of the national database.

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Abbreviations

BGS	British Geological Survey
CB	Clare Basin
Corine	Co-ordination of Information on the Environment (database)
CRS	Coulomb rate-state
DCCAE	Department of Communications, Climate Action and Environment
DfE	Department for the Economy
DWI	Deep water injection
EPA	Environmental Protection Agency
ESA	European Space Agency
GNSS	Global Navigation Satellite System
InSAR	Interferometric synthetic aperture radar
INSN	Irish National Seismic Network
ISBAS	Intermittent Small Baseline Subset
JRP	Joint Research Programme
M	Moment magnitude
ML	Local magnitude
Mw	Seismic moment magnitude
NCB	Northwest Carboniferous Basin
NDC	National Data Centre
PS	Persistent scatterer
SAR	Synthetic aperture radar
SBAS	Small Baseline Subset
UCD	University College Dublin
UGEE	Unconventional gas exploration and extraction

Summary Report 2: Baseline Characterisation of Seismicity

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Unconventional gas exploration and extraction (UGEE) involves hydraulic fracturing (“fracking”) of low permeability rock to permit the extraction of natural gas on a commercial scale from unconventional sources, such as shale gas deposits, coal seams and tight sandstone.

The UGEE Joint Research Programme (JRP) (**www.ugeeresearch.ie**) is composed of five interlinked projects and involves field studies (baseline monitoring of water and seismicity), as well as an extensive desk-based literature review of UGEE practices and regulations worldwide. The UGEE JRP was designed to provide the scientific basis that will assist regulators - in both Northern Ireland and Ireland - to make informed decisions about whether or not it is environmentally safe to permit UGEE projects/operations involving fracking. As well as research in Ireland, the UGEE URP looks at and collates evidence from other countries.

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List of Outputs:

- Final Report 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems
- Summary Report 1: Baseline Characterisation of Groundwater, Surface Water and Aquatic Ecosystems
- Final Report 2: Baseline Characterisation of Seismicity
- Summary Report 2: Baseline Characterisation of Seismicity
- Final Report 3: Baseline Characterisation of Air Quality
- Summary Report 3: Baseline Characterisation of Air Quality
- Final Report 4: Impacts & Mitigation Measures
- Summary Report 4: Impacts & Mitigation Measures
- Final Report 5: Regulatory Framework for Environmental Protection
- Summary Report 5: Regulatory Framework for Environmental Protection
- UGEE Joint Research Programme Integrated Synthesis Report

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