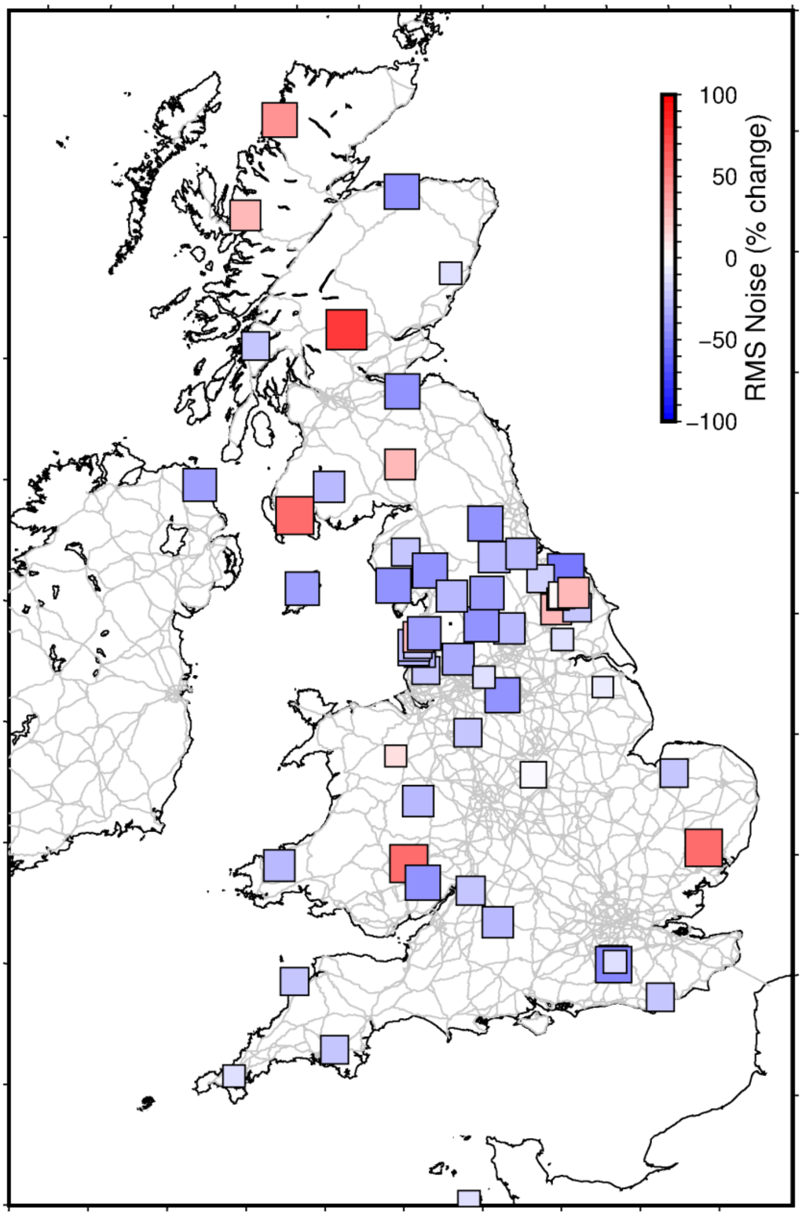
Earthquake Seismology 2020/2021

BGS National Earthquake Information Service

Thirty-second Annual Report



BRITISH GEOLOGICAL SURVEY

OPEN REPORT OR/21/033

Earthquake Seismology 2020/2021

B. Baptie (editor)

Key words

Monitoring, Earthquakes, Seismology.

Front cover

Percentage reduction in the RMS amplitude of daytime seismic noise at BGS stations across the UK in the first few weeks of lockdown compared with the rest of 2020.

Bibliographical reference

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Contents

Summary

The British Geological Survey (BGS) operates a network of seismometers throughout the UK to acquire seismic data on a long-term basis. The aims of the National Earthquake Information Service (NEIS) project are to develop and maintain a national database of seismic activity in the UK for use in seismic hazard assessment, and to provide a near-immediate response to the occurrence, or reported occurrence, of significant events. The project is supported by a group of organisations under the chairmanship of the Office for Nuclear Regulation (ONR) with major financial input from the Natural Environment Research Council (NERC).

The 32nd year of the project was notable for the global COVID-19 pandemic, which created some significant challenges. Despite these challenges, we continued to operate the national seismic monitoring network efficiently and effectively, carrying out critical fieldwork and using a well-established and secure method for remotely accessing the BGS computer network. Data latency was generally low, less than one minute most of the time, and while data completeness was less than the previous year because of restrictions on fieldwork, the impact of any failures at individual monitoring sites was mitigated by the high level of redundancy in our data acquisition.

All significant events were reported rapidly to the Customer Group through seismic alerts sent by e-mail. The alerts were also published on the Internet (http://www.earthquakes.bgs.ac.uk).

Four papers have been published in peer-reviewed journals, three BGS reports prepared, along with one other commissioned report and two papers were published in conference proceedings. This included studies of induced seismicity and revised seismic hazard maps for the UK. We have continued to collaborate widely with academic partners across the UK and overseas on a number of research initiatives.

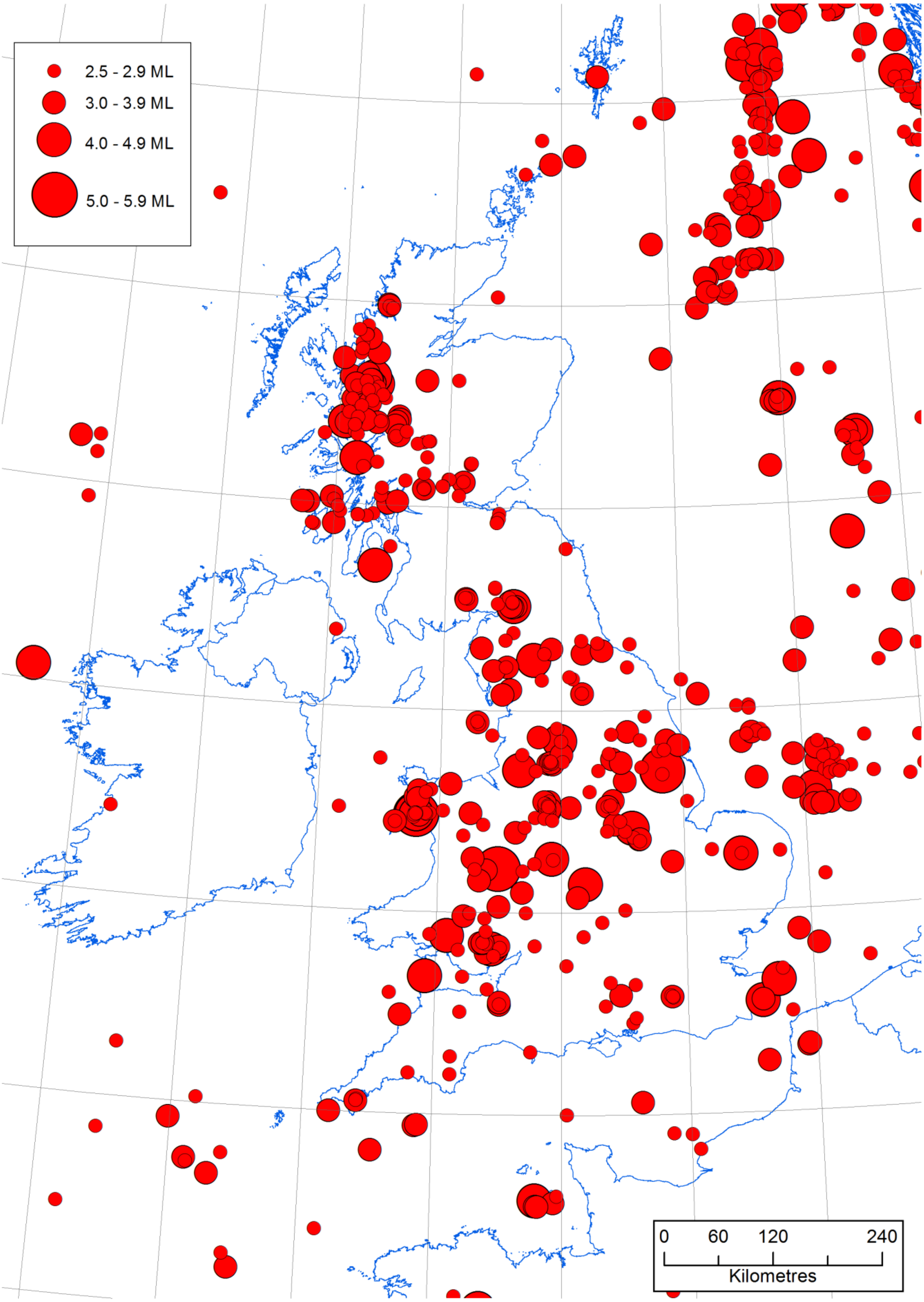
Introduction

The BGS Seismic Monitoring and Information Service has developed because of the commitment of a group of organisations with an interest in the seismic hazard of the UK and the immediate effects of felt or damaging vibrations on people and structures. The supporters of the project, drawn from industry and central and local government, are referred to as the Customer Group.

Almost every week, seismic events are reported to be felt somewhere in the UK. A small number of these prove to be sonic booms or are spurious, but a large proportion are natural earthquakes often felt at intensities which cause concern and, occasionally, some damage. The Information Service aims to rapidly identify these various sources and causes of seismic events, which are felt or heard.

In an average year, about 150 earthquakes are detected and located by BGS with around 15% being felt by people. Historically, the largest known British earthquake occurred on the Dogger Bank in 1931, with a magnitude of 6.1 ML. Fortunately, it was 60 miles offshore, but it was still powerful enough to cause minor damage to buildings on the east coast of England. The most damaging UK earthquake known in the last 400 years was in the Colchester area (1884) with the modest magnitude of 4.6 ML. Some 1200 buildings needed repairs and, in the worst cases, walls, chimneys and roofs collapsed.

Long term earthquake monitoring is required to refine our understanding of the level of seismic hazard in the UK. Although seismic hazard and risk are low by world standards, they are by no means negligible, particularly with respect to potentially hazardous installations and sensitive structures. The monitoring results help assess the level of precautionary measures which should be taken to prevent damage and disruption to new buildings, constructions and installations which otherwise could prove hazardous to the population. For nuclear sites, seismic monitoring provides objective information to verify the nature of seismic events or to confirm false alarms, which might result from locally generated instrument triggers.



Epicentres of earthquakes with magnitudes 2.5 ML or greater, for the period 1979 to March 2021.

Introduction

Monitoring Network

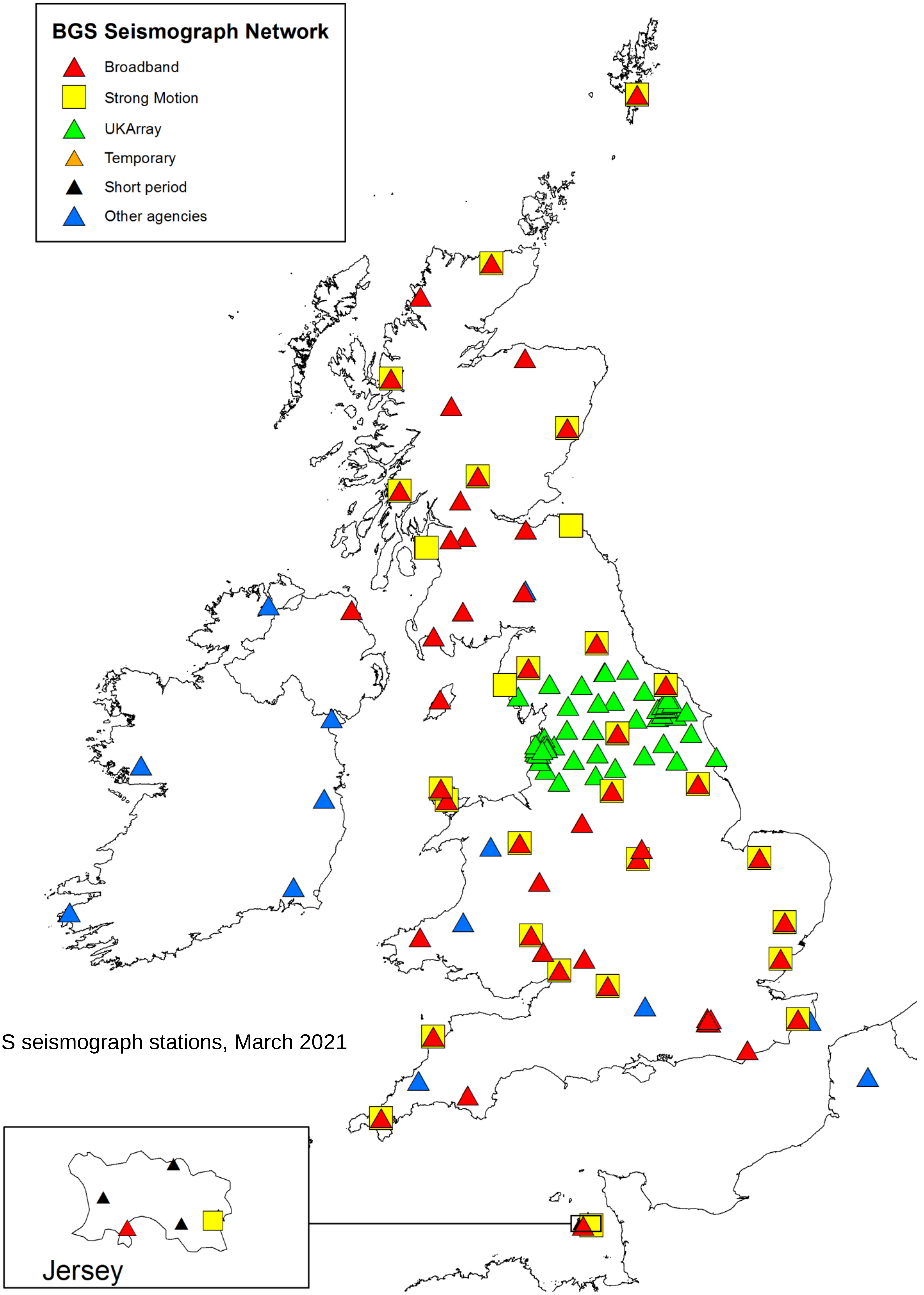
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late 1990s, the number of stations reached its peak of 146, with an average spacing of 70 km. The current network consists of both broadband seismometers and strong motion accelerometers and provides high quality data for both monitoring and scientific research.

In the late 1960s, BGS installed a network of eight seismograph stations in the lowlands of Scotland, with data transmitted to the recording site in Edinburgh by radio, over distances of up to 100 km. Data were recorded on a slow running FM magnetic tape system. Over the next thirty years the network grew, both in response to specific events, such as the Lleyn Peninsula earthquake in 1984, and because of specific initiatives, such as monitoring North Sea seismicity, reaching a peak of 146 stations by the late 1990s.

The network was divided into several sub-networks, each consisting of up to ten seismometers radio-linked to a central site, where the continuous data were recorded digitally. Each sub-network was accessed several times each day using Internet or dial-up modems to transfer any automatically detected event to the BGS offices in Edinburgh. Once transferred, the events were analysed to provide a rapid estimate of location and magnitude.

However, scientific objectives, such as measuring the attenuation of seismic waves, or accurate determination of source parameters, were restricted by both the limited bandwidth and dynamic range of the seismic data acquisition. The extremely wide dynamic range of natural seismic signals means that instrumentation capable of recording small local micro-earthquakes will not remain on scale for larger signals.

The network currently consists of 47 broadband seismometers at stations across the UK along with 33 strong motion accelerometers with high dynamic range for recording strong signals. Eight short period sensors also remain in use. In addition, 36 stations have been installed across the north of England as part of the UKArray project (34 broadband sensors and two strong motion sensors and there are a further five temporary sensors in southeast England (all broadband) to monitor the Newdigate sequence.



BGS seismograph stations, March 2021

Achievements

Network Performance

The COVID-19 pandemic created some significant challenges. We were able to address these challenges by gaining essential worker status to allow us to carry out critical work, using a well-established and secure method for remotely accessing our computer networks and the existing high level of redundancy in our data acquisition.

Although the Covid-19 lockdown limited the amount of fieldwork we were able to carry out, BGS management, UKRI (our parent body) and BEIS quickly recognised the seismic monitoring network is important national infrastructure and our engineers were given essential worker status to allow them to make critical maintenance trips and to travel to our lab and workshop to prepare and test equipment.

In addition, we already had a well-established and secure method for accessing the BGS network from our home computers. This allowed us to access our data acquisition and processing computers remotely to check the status of all our monitoring stations and data processing.

There is also a high level of redundancy in our data acquisition, with duplicate systems in the BGS offices in Edinburgh and Nottingham. Should there be a failure at one site, the system at the other should continue to run completely independently. Our data acquisition at both sites is also connected to back-up generators should there be any failure in the power supply.

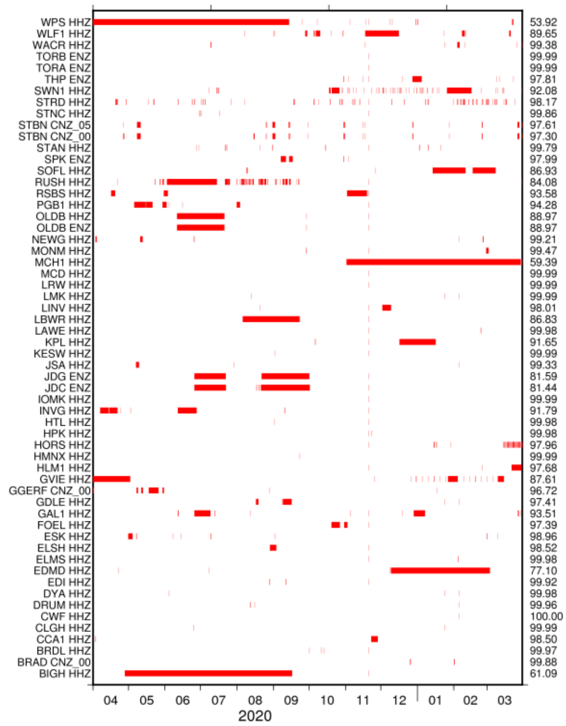
In 2020/21 a total of 348 station faults were resolved through a mixture of remote access, station visits by our own staff, the use of sub-contractors and landowners working under our direction. In total, 50 person days were spent on fieldwork. This low number is a result of Covid restrictions and was partly mitigated by increased use of sub-contractors. There is also a backlog in repairs awaiting the easing of Covid restrictions, ranging from stations that currently have only partial functionality to complete loss of data. The ongoing Covid situation also delayed the recovery of temporary stations as well as delaying work on new stations.

The identification of faults is still mostly based on automated analysis of a variety of data, a process that we have continued to refine throughout this period. In particular, the new borehole sensors we manage across the UK have required an entirely new set of automated processes.

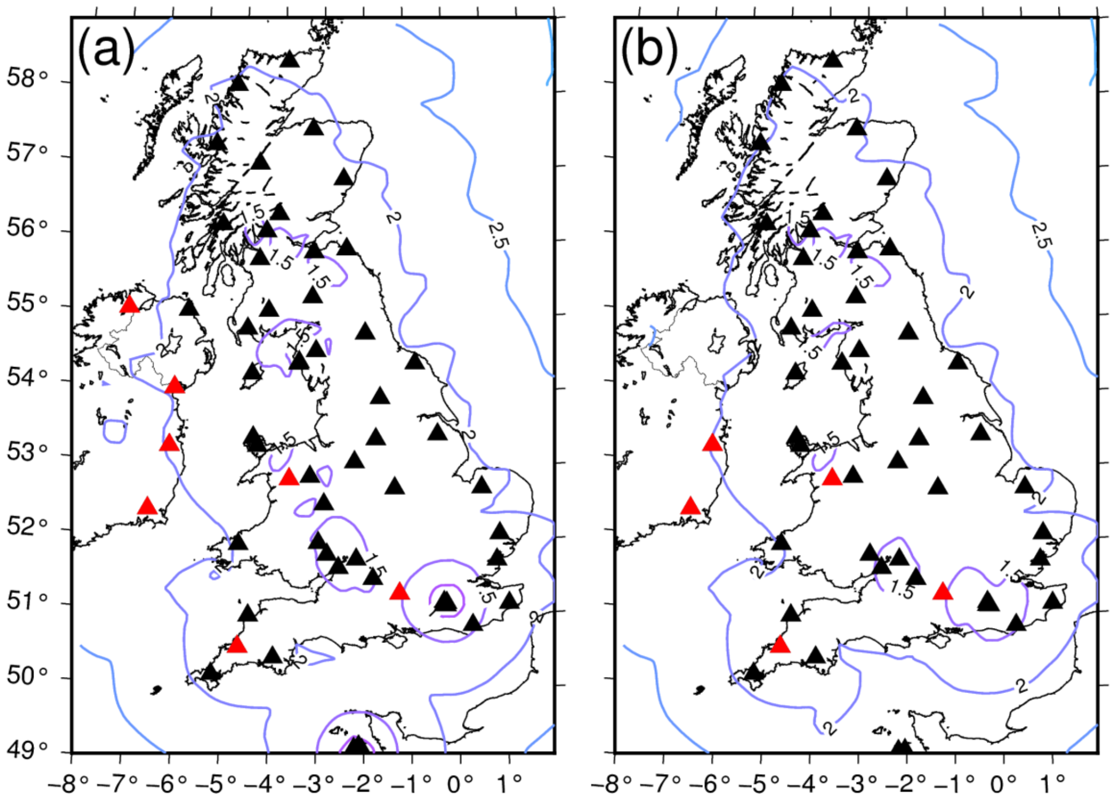
Continuous data from all our stations are archived and the completeness of these data can be easily checked to gain an accurate picture of network performance. For 2020-2021, data was 95% complete at 64% of stations, 90% complete at 74% of stations and 85% complete at 84% of stations, which is a decline on the previous year when data was 95% complete at 72% of stations and more than 90% complete for over 83% of stations.

The worst performing broadband stations were WPS, Wylfa (54%), SPK, Sella Park (58%), MCH1, Michaelchurch (60%), BIGH, Bighouse (61%) and EDMD, Edmundbyers (77%). Most of these outages were the result of being unable to access sites due to COVID-19 restrictions. SPK was shut down by site owners whilst they carried out work on site.

In addition, fewer than two stations were down at the same time 84% of the time and less than four down 99% of the time. A snapshot of the impact that this has on the overall detection capability of the network can be obtained by calculating detection capability maps with and without the stations that were down at any time. For example, on 28 April 2021, 13 stations were down at the same time.



Data completeness for all broadband stations that operated throughout 2020/2021. Data are more than 95% complete at 64% of stations, 90% complete at 74% of stations and 85% complete at 84% of stations.



Detection capability of the network with (a) all stations operational (b) with SPK, CLGH, MCH1, JLP, JRS, JVM, STAN, IGLA, ILTH, HORS, HLM1, IDGL and GVIE down. The contours show earthquake magnitudes (ML) that can be detected. Signal amplitudes must exceed the background noise level by a factor of two at five or more stations. A noise amplitude of 10 nm is assumed for all stations. Red triangles show stations operated by other agencies.

Information Dissemination

It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received alerts by e-mail whenever an event was felt or heard by more than two individuals.

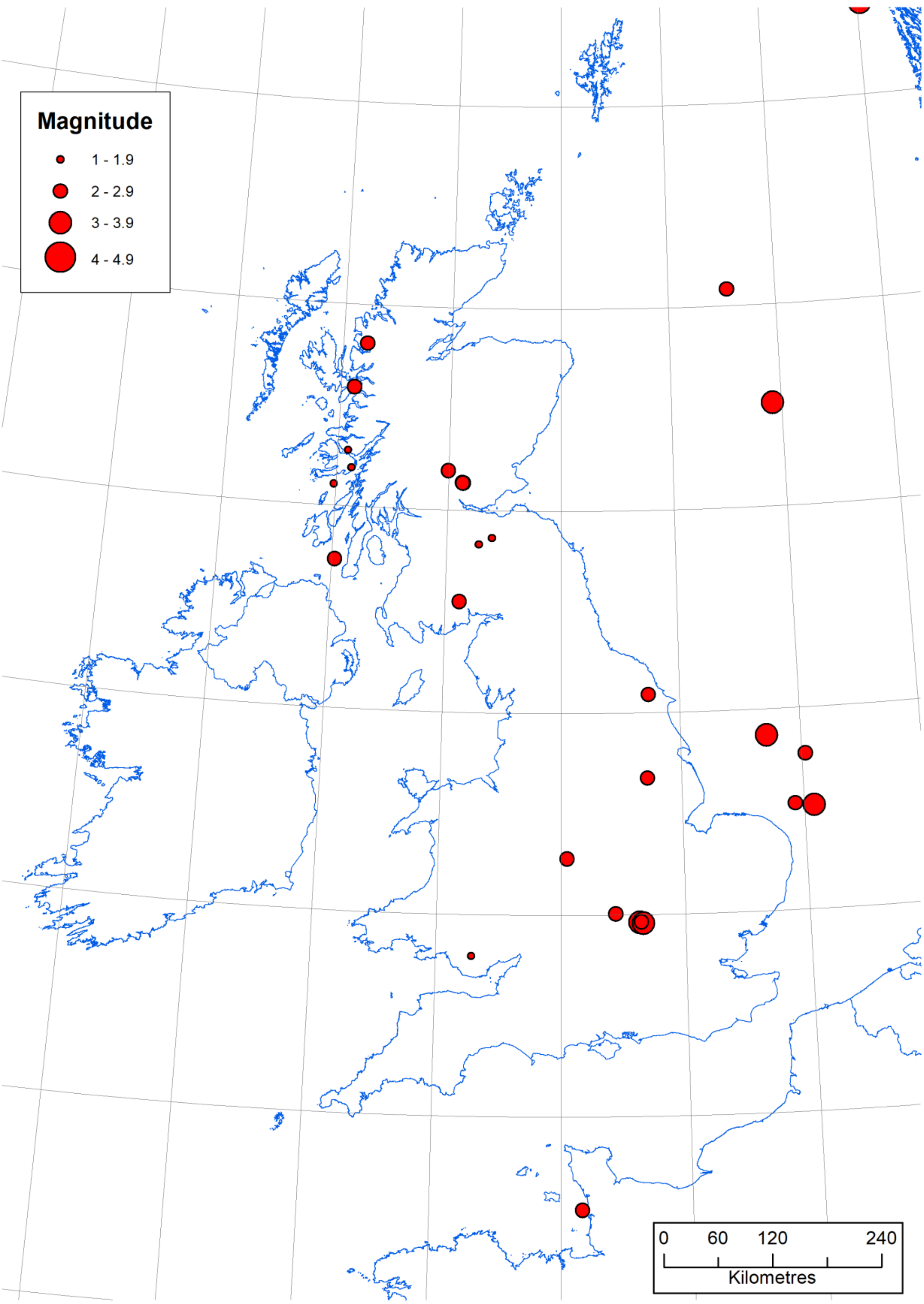
Alerts were issued for 41 UK events within the reporting period. Alerts for all local earthquakes were issued to Customer Group members within two hours of a member of the 24-hour on-call team being notified. The alerts include earthquake parameters, reports from members of the public, damage, and background information. Thirty of the alerts were for earthquakes on mainland Britain and a further nine were for earthquakes offshore in the waters around the British Isles. The two remaining alerts were for sonic booms.

The Earthquake Seismology web pages are directly linked to our earthquake database providing near real-time lists of significant earthquake activity, together with automatically generated pages for each event.

Our web pages also incorporate our automatic macroseismic processing system, which remains a key part of our response to felt events and is used to produce macroseismic maps for the seismology web pages. These are updated in near real-time as data are contributed. We received over 1900 replies following the magnitude 3.5 ML earthquake near Leighton Buzzard on 8 September 2020 and another 499 following a magnitude 3.0 event in the same location on 22 September. We received over 200 replies following a magnitude 2.2 ML earthquake near Comrie on 6 June 2020 and 85 for the magnitude 2.5 ML near Blackford, Perthshire on 4 October 2020. We received 92 replies following a magnitude 1.9 ML earthquake near Skirling in the Scottish Borders.

The final version of the annual report for 2019-2020 was circulated to all Customer Group members in December 2020. Three newsletters were circulated to Customer Group members for the time periods April to July, August to November and December to March. A briefing note was issued in April to outline how the service was dealing with the Covid-19 lockdown to ensure that essential information on earthquakes or other seismic events was being provided.

The NEIS project strategy was published in 2019 and set out a forward plan with objectives, actions and deliverables that would be used to map progress and update future iterations of the strategy. In order to track our progress, we prepared a strategy action log, with help from a number of customers, that contains a summary of each action along with progress updates, delivery dates and current status. These are split into sections that correspond to parts of the forward plan in the project strategy document.



Events in the reporting period (1 April 2020 – 31 March 2021) for which alerts have been issued. Circles are scaled by magnitude.

Achievements

Communicating Our Science

An important part of the BGS mission is to provide accurate, impartial information in a timely fashion to our stakeholders, the public and the media. We promote understanding of Earth Sciences by engaging with the public and other audiences and by creating dynamic web pages with background information and topical content.

Reductions in background seismic noise during the COVID-19 pandemic was widely reported by seismologists around the world (e.g. Lecoq et al., 2020) as a result of lockdown measures and corresponding decreases in noise sources such as traffic and industrial machinery. This effect was also recorded by seismometers across the UK and received some media attention with articles in the BBC web pages, the Guardian newspaper and elsewhere, as well as several interviews for media outlets.

A comparison of the average daytime noise levels at seismic stations in the UK during the initial Covid-19 lockdown with the average noise levels in the period before showed reductions in noise levels at most stations of between 10-50%. Such a reduction in seismic noise could help us to see signals from earthquakes that are normally buried in the noise and improve the detection of small earthquakes. However, as lockdown measures eased throughout the year, noise levels gradually returned to pre-lockdown levels.

New national seismic hazard maps for the UK were published in November 2020. The release of the maps was accompanied by blog posts on both the Institute of Civil Engineers and the main BGS web site.

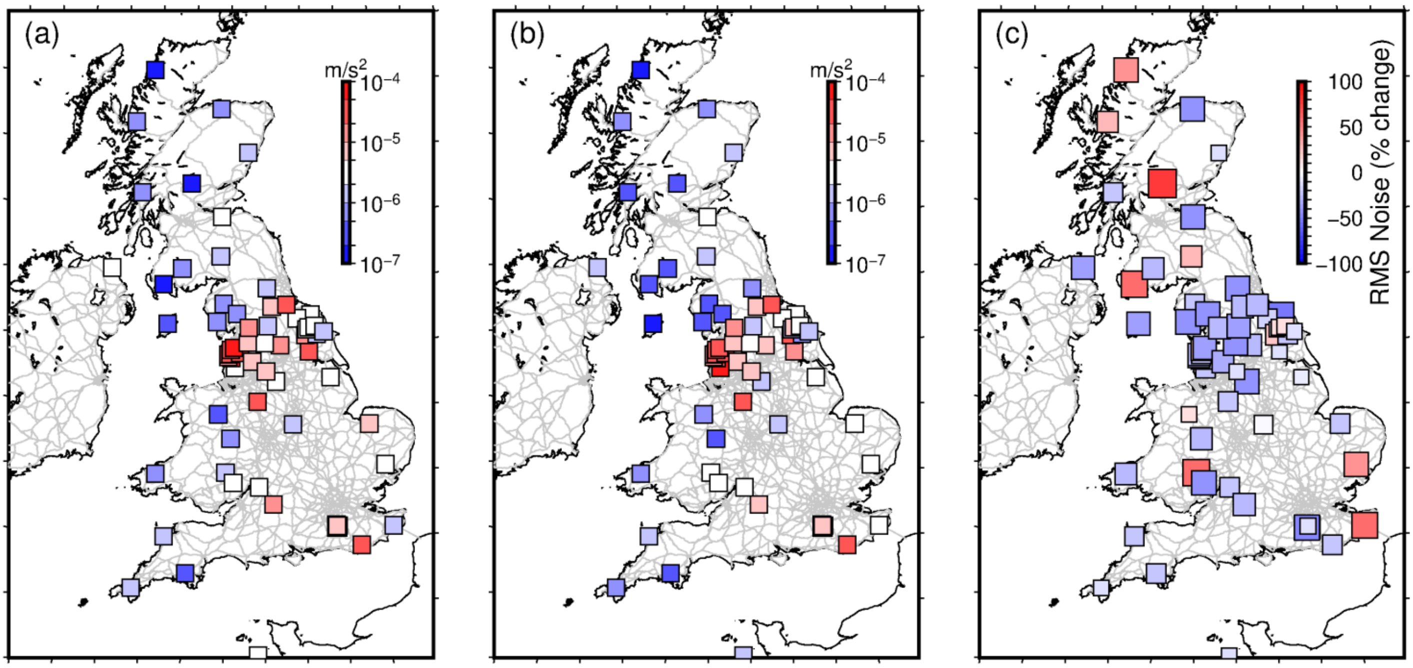
Ilaria Mosca will give a virtual presentation on the new national seismic hazard maps at the evening meeting of the Society for Earthquake and Civil Engineering Dynamics at the Institute of Civil Engineers, London on 26 May. You can download the maps along with the earthquake catalogue, the seismic source characterisation model, and the ground motion characterisation model, as well as output data for different ground motion measures and return periods at https://quakes.bgs.ac.uk/hazard/UKhazard.html.

There was considerable public and media interest following both the Leighton Buzzard and Blackford earthquakes. Davie Galloway, Glenn Ford and Richard Luckett all gave interviews to journalists. Davie Galloway and Glenn Ford also gave several interviews following the magnitude 2.2 ML earthquake near Comrie, Perth and Kinross, on 6 June. Brian Baptie recorded a short interview with STV on earthquakes in Scotland. We also responded to questions about the Leighton Buzzard earthquakes from the local Member of Parliament.

BGS remains a principal point of contact for the public and the media for information on earthquakes and seismicity, both in the UK and overseas. During 2020-2021, at least 980 enquiries were answered. These were all logged using the BGS enquiries tracking database. Many of these were from the media, which often led to TV and radio interviews, particularly after significant earthquakes.

The seismology web site continues to be widely accessed, with an average of over 25,000 visitors logged each month.

The Seismology web pages are intended to provide earthquake information to the public as quickly as possible. Earthquake lists, maps and specific pages are generated and updated automatically whenever a new event is entered in our database or when the parameters for an existing event are modified. We also have a database search page that allows users to search our database for basic earthquake parameters within a given geographic or magnitude range. We have also continued to provide displays of real-time data from most of our seismic stations that allow users to check activity or look for specific events. In addition, we continue to add event-specific content for significant earthquakes in the UK and around the world.



RMS amplitude of daytime seismic noise at BGS stations across the UK in the first few weeks of lockdown (b) compared with the rest of 2020 (a). Amplitudes are calculated in the 4-40 Hz frequency band between 0700 and 1900 UTC. The percentage difference between the two (c) shows that most stations experienced reductions in noise levels of anywhere between 10-50%. Often the noisiest stations show the greatest reductions, for example, temporary sensors around Blackpool and other urban areas. Although some quieter stations show increases in noise level, for example, stations in northwest Scotland, the noise levels before and after lockdown remain very low and the increase is probably a result of natural variability in background noise.

Collaboration and Data Exchange

Data from the seismograph network are freely available for academic use and we have continued to collaborate with researchers at academic institutes within the UK throughout the past year, as well as exchanging data with European and world agencies.

In March 2020, the Oil and Gas Authority (OGA) commissioned BGS together with researchers from the University of Bristol to undertake additional research to understand and learn from the induced seismicity observed at Preston New Road in 2018 and 2019.

The first of these studies Mancini et al (2020) examined the feasibility of statistically forecasting the microseismicity observed during and after hydraulic fracturing operations in the PNR-1z and PNR-2 well. Three models were compared: a standard ETAS (Epidemic Type Aftershock Sequence) model, commonly used for modelling tectonic seismicity, along with two modified ETAS models where the background rate was proportional to the fluid injection rate. A model in which the background seismicity rate was driven by injection rates during specific hydraulic fracture stages was found to perform best. These results suggest that such models have potential to provide informative time-dependent forecasts for operators and decision-makers.

In the second study Baptie et al. (2020) examined the magnitude estimates from the downhole seismicity catalogues from PNR-1z and PNR-2 wells. They find that the moment magnitudes (Mw) from each have a different relationship with the surface local magnitudes (ML) and that the downhole Mw values are significantly less than the expected value of Mw based on the surface ML. The moment magnitudes in the downhole catalogues were corrected using the observed relationship between surface and downhole moment magnitude, which resulted in increases to measured activity rate.

The NERC-NSF project “The Central Apennines sequence under a New Microscope” entered its final year. The project is led by Margarita Segou from BGS and brings together scientists from the UK (BGS, Universities of Edinburgh and Bristol), the US (University of Stanford, US Geological Survey, Lamont-Doherty Observatory Columbia University) and Italy (INGV). New machine learning and template matching approaches (Tan et al., 2021) have been applied to data recorded during the sequence to improve detection capability and produce large, data-rich event catalogues. These are then being used to explore how physics-based earthquake forecasts during such sequences can be improved (Mancini et al., 2019; Mancini et al., 2021).

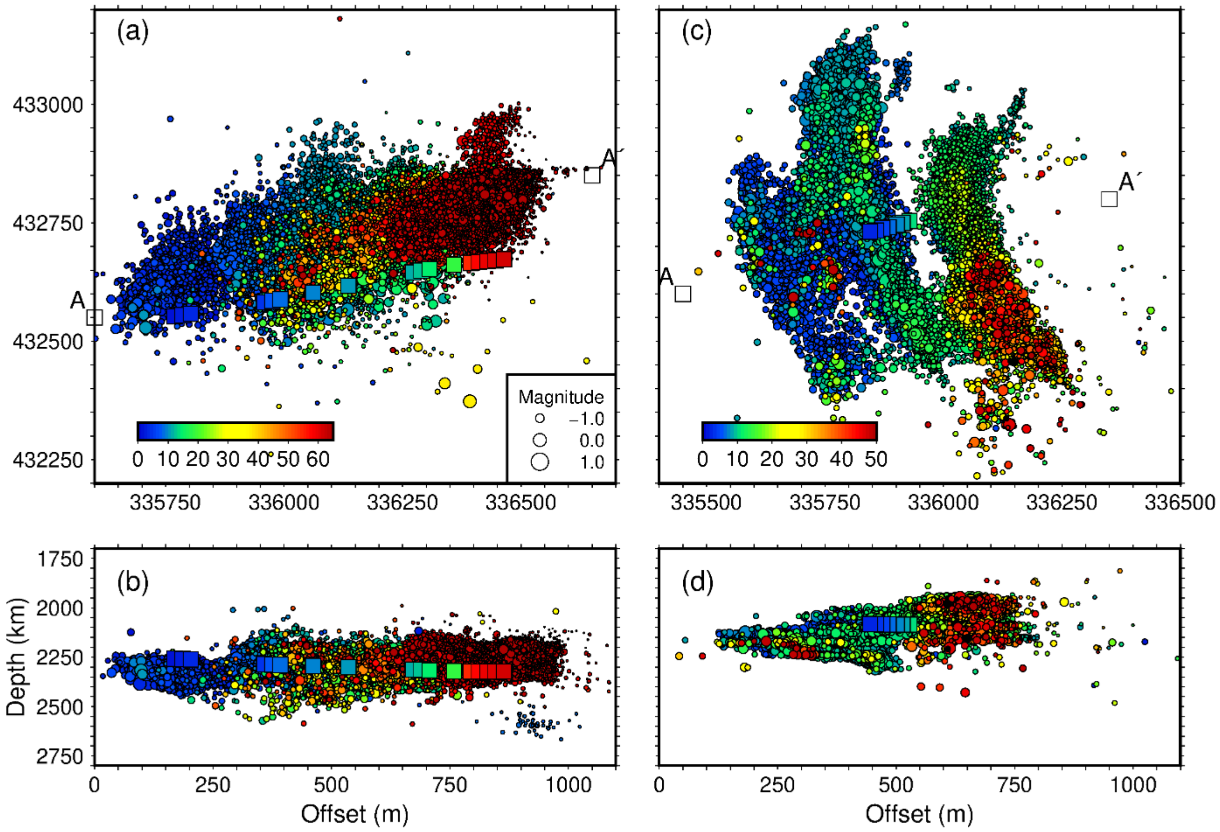
Atalay Ayele from the Institute of Geophysics, Space Science and Astronomy (IGSSA) at the University of Addis Ababa in Ethiopia has worked with Richard Luckett (BGS) on recent seismicity at Fentale volcano in Ethiopia and with Ilaria Mosca (BGS) on developing seismic hazard assessments for the Main Ethiopian Rift.

The NERC funded REMIS (Reliable Earthquake Magnitudes for Induced Seismicity) project ended in October 2020. The project was a collaboration between BGS and researchers at the Universities of Leeds and Edinburgh and used a non-linear Bayesian approach to estimate joint probability density functions of earthquake locations, magnitudes, and seismic velocities in the subsurface.

Brian Baptie is a co-I of the NERC funded Equipt4Risk project, which is examining potential risks to groundwater, air quality and the built environment from shale-gas development. As part of this he worked with researchers at universities of Stanford, Miami, Calgary and the USGS on a review of hydraulic fracture induced seismicity (Schultz et al, 2020).

BGS were partners in a joint project commissioned by Radioactive Waste Management to assess the potential likelihood and possible consequence of induced seismicity for a generic Geological Disposal Facility (GDF). The study concluded that although a GDF has the potential to induce seismicity, this can be mitigated through appropriate design.

BGS continues to exchange data with other agencies to help improve source parameters for regional and global earthquakes. Phase data are distributed to the European-Mediterranean Seismological Centre (EMSC), the National Earthquake Information Centre (NEIC) at the USGS and the International Seismological Centre (ISC) to assist with location of earthquakes and rapid determination of source parameters. Waveform data are transmitted to both the European Integrated Data Archive and IRIS (Incorporated Research in Seismology).



Maps of all events in the microseismic catalogue recorded during operations in PNR-1z (a) and PNR-2 (c). Events are coloured by time in days from the start of operations and scaled by magnitude. The coloured squares in (a) show the locations of the sleeves that were hydraulically fractured in PNR-1z and PNR-2. The squares are coloured using the same colour scale as the events. Axes show British National Grid Eastings and Northings. (b) and (d) show depth cross-section showing event depths along the profile A-A´.

Seismic Activity

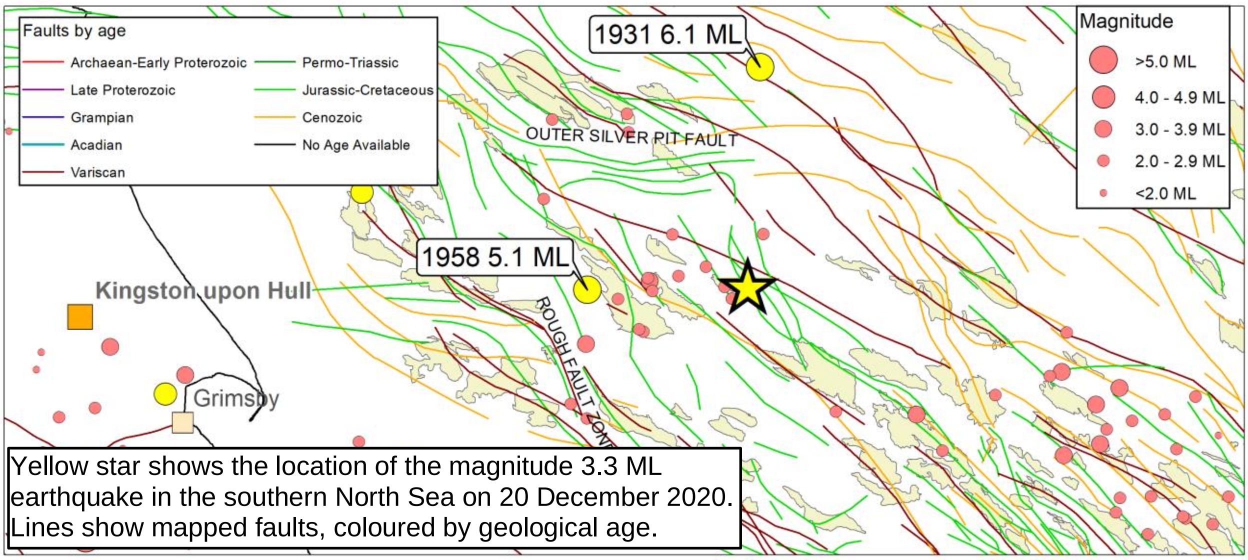
The details of all earthquakes, felt explosions and sonic booms detected by the BGS seismic network have been published in monthly bulletins and compiled in the BGS Annual Bulletins.

There were 271 local earthquakes located by the monitoring network during 2020-2021. This does not include the seismicity induced by fluid injection at the United Downs Deep Geothermal Project (UDDGP) in Cornwall. Thirty of these had magnitudes of 2.0 ML or greater and seven had magnitudes of 3.0 ML or greater. Fifteen events, with a magnitude of 2.0 ML or greater, were reported felt, together with a further 21 smaller ones, bringing the total to 36 felt earthquakes in 2020-2021.

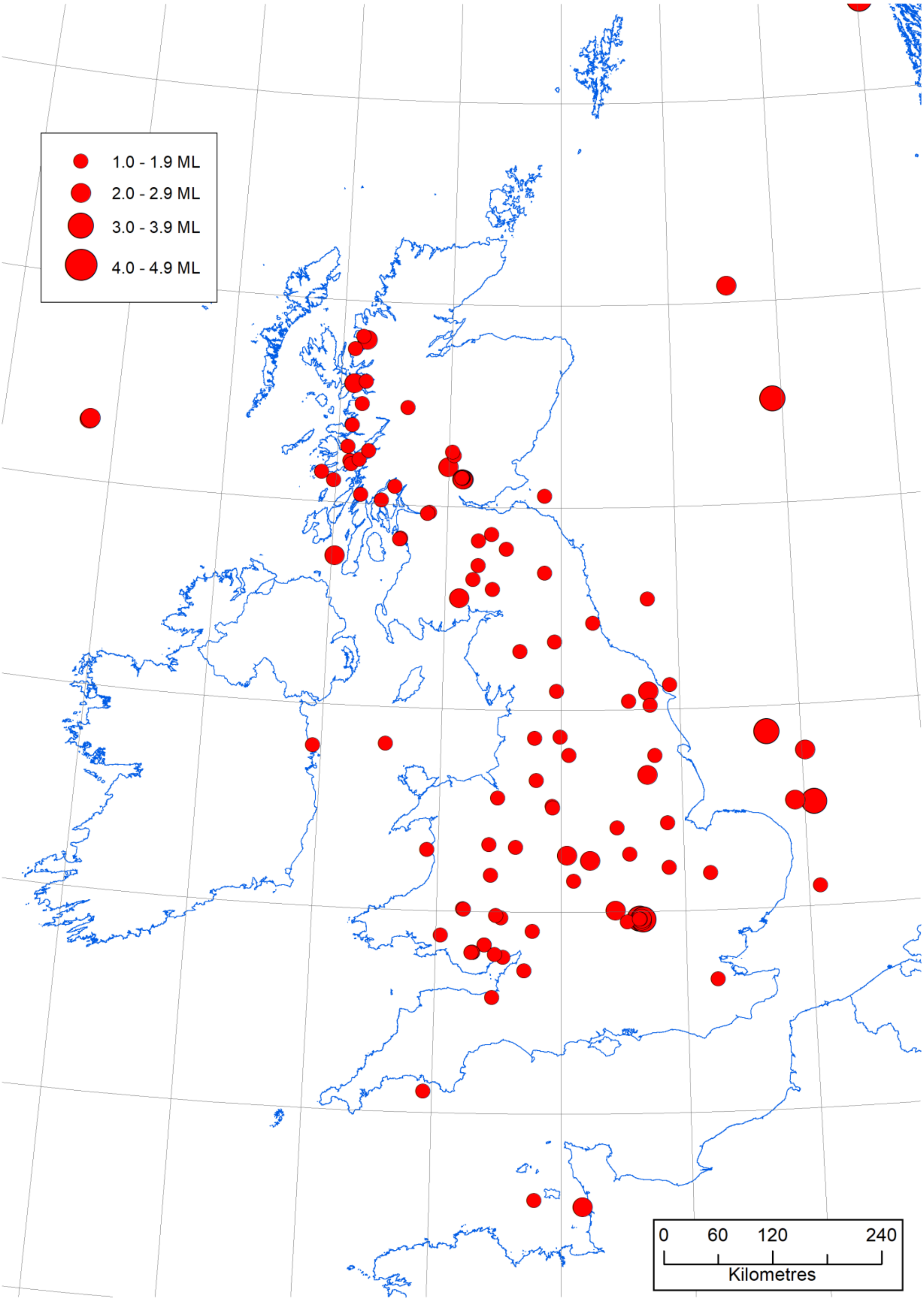
The largest onshore earthquake in 2020-2021 was a magnitude 3.5 ML event that occurred close to Leighton Buzzard, Bedfordshire on 8 September. The event was strongly felt, with a maximum intensity of 6 EMS. It was the largest earthquake in this part of England since a magnitude 4.0 ML near Warwick on 23 September 2000, around 90 km to the northwest.

A swarm of thirty-three earthquakes, ten of which were felt by local residents, were detected in the Blackford area, Perth & Kinross during 2020 with magnitudes ranging between 0.3 ML and 2.5 ML. The largest, magnitude 2.5 ML, occurred on 4 October at 18:43 UTC. Reports from residents of Blackford and other nearby villages state that “windows rattled”, people “felt a thud” and “heard a loud bang”, “like an explosion”.

Two magnitude 3.3 ML earthquakes were detected in southern North Sea. The first occurred on 23 April 2020 and was located approximately 65 km NNE of Lowestoft. It occurred in an area where there has been considerable historic seismicity and is in an area of long term gas production. The second occurred on 20 December 2020 and was approximately 100 km east of Grimsby. This event occurred in an area where there have been a number of both historical and instrumentally recorded earthquakes. The epicenter was 40 km south of the magnitude 6.1 ML Dogger Bank earthquake in 1931 and 30 km east of a magnitude 5.1 ML earthquake in 1958. A magnitude 3.1 ML earthquake was detected in the Central North Sea on 14 February 2021.



Yellow star shows the location of the magnitude 3.3 ML earthquake in the southern North Sea on 20 December 2020. Lines show mapped faults, coloured by geological age.



Epicentres of all earthquakes in and around the UK detected in the reporting period
(1 April 2020 – 31 March 2021).

Leighton Buzzard, Bedfordshire

Six earthquakes were recorded in September 2020 near Leighton Buzzard, Bedfordshire, an area with little significant historical seismicity. The largest of these had a magnitude of 3.5 ML and was widely felt with a maximum intensity of 6 EMS.

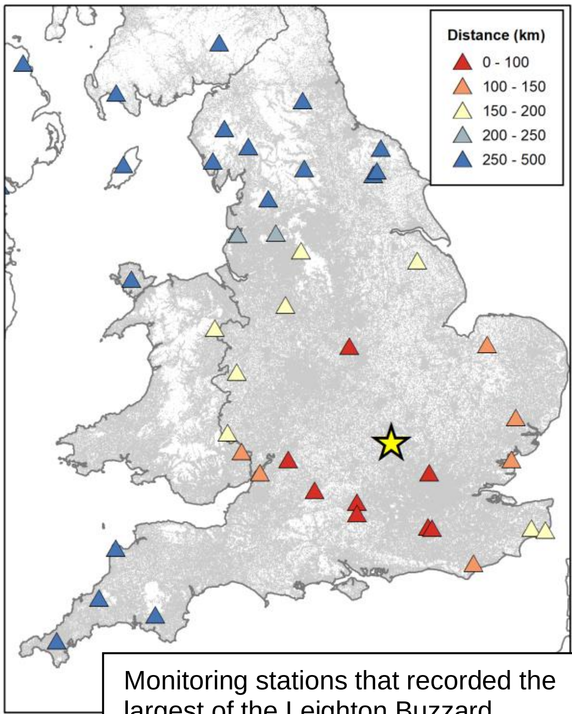
The largest onshore earthquake in 2020-2021 was a magnitude 3.5 ML event on 8 September at 08:45 UTC, a few kilometres to the west of Leighton Buzzard, Bedfordshire. We received over 1950 reports from members of the public who felt the earthquake. Most of the reports were from around Bedfordshire, Buckinghamshire, and Hertfordshire at distances of up to 25 km of the epicentre. Typical comments included: “it felt like the whole house was shaking”; “all the windows rattled”, “there was a heavy vibration”, and “it was like a large explosion”. A maximum intensity of 6 EMS was assigned to this event.

A further five events were recorded in the same area during September 2020. The first of these was on 13 September at 23:20 UTC, with a magnitude of 2.1 ML. It was felt up to around 5 km from the epicentre, with a maximum intensity of 3 EMS. Magnitude 1.3 ML and 1.1 ML earthquakes were recorded on 14 and 15 September, at 06:11 UTC and 03:28 UTC, respectively. Neither of these appear to have been felt.

On 22 September at 08:32 UTC, A magnitude 3.0 ML event occurred. We received around 500 reports from people who felt the earthquake. Most of these reports were from within around 20 km of the epicentre. A maximum intensity of 4 EMS was assigned to this event. Later that day, at 12:39 UTC, a magnitude 2.1 ML event occurred and was felt with a maximum intensity of 3 EMS in an area within around 5 km of the epicentre.

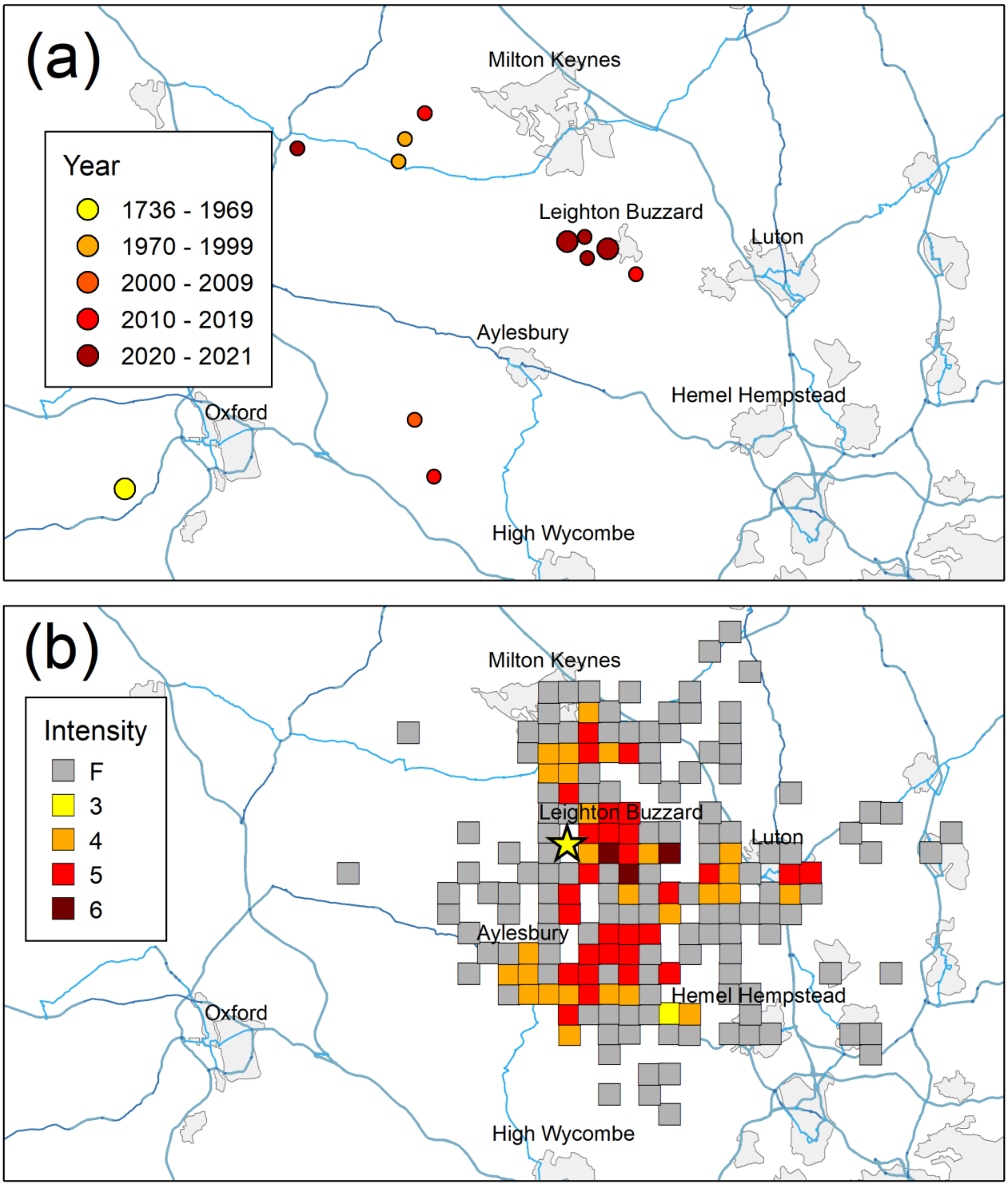
There is relatively little significant historical seismicity in this part of the UK. An earthquake with a magnitude of 2.0 was recorded near Dunstable in 2010 and an event with a magnitude 2.2 occurred near Brackley, 30 km west of Leighton Buzzard, on 4 January 2020. Neither of these were felt. The closest event with a similar magnitude, 3.4 ML, was near Oxford in 1764. It was also widely felt. More recently there was a magnitude 2.9 near Oxford in 1986.

The closest BGS monitoring station to the epicentre was 87 km away at Swindon, although we also had access to real-time



Monitoring stations that recorded the largest of the Leighton Buzzard earthquakes. Symbols are coloured by distance from the epicentre.

data from monitoring stations run by AWE at distances of 67 and 76 km away. As a result, although the epicentres of these events are well-constrained, event depths are less well constrained and subject to uncertainties of ± 8 km. This highlights some of the limitations of the current monitoring network in this densely populated part of Britain.



(a). Earthquakes recorded near Leighton Buzzard, Bedfordshire. Events are coloured by year of occurrence. (b) Macroseismic intensities calculated for the magnitude 3.5 ML earthquake on 8 September. Intensities are calculated in 2 km grid squares from 1750 reports from people who felt the earthquake. A minimum of five observations is needed in any grid square to calculate a value of intensity, otherwise the value is recorded as “Felt”, but no intensity is calculated (grey squares).

Seismic Activity

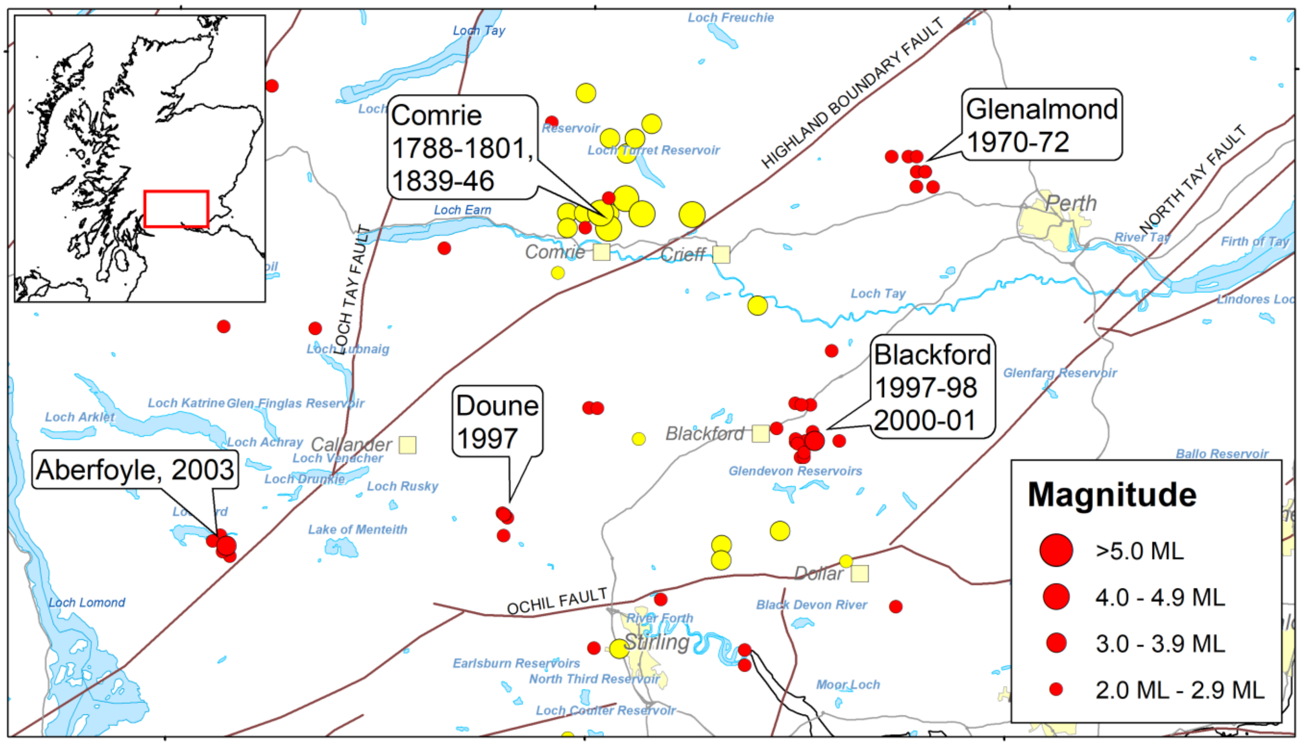
Blackford, Perthshire

Twenty-nine earthquakes were recorded near Blackford, Perthshire between September and November 2020. Three of these had magnitudes of greater than 2.0 ML and the largest was a magnitude 2.5 ML on 4 October. Nine of the earthquakes were felt by people in Blackford, Gleneagles and Auchterarder. The maximum intensity was 3 EMS.

This part of Scotland has experienced numerous such earthquake sequences or “swarms” in the past. A magnitude 4.6 ML earthquake near Comrie, 18 km to the northwest, on 7 September 1801 was preceded by several hundred felt events over a period of several years (Musson, 1994). Similarly, another 14 earthquakes greater than 3.0 ML were reported in the same area between 1839 and 1841. The largest, on 23 October 1839, had a magnitude of 4.8 ML was associated with a breach of the Earl’s Burn dam to the southwest of Stirling (Musson, 1991; Environment Agency, 2011). A magnitude 4.4 ML near Comrie in 1846 was preceded by three foreshocks with magnitude greater than 3.0 ML.

More recently, sequences of smaller earthquakes nearby were recorded at Glenalmond (1970-1972), Doune (1997) and Aberfoyle (2003). The latter sequence is described in Ottemoller and Thomas (2007).

In addition to the most recent activity, there have been four other distinct swarms immediately around Blackford. Between

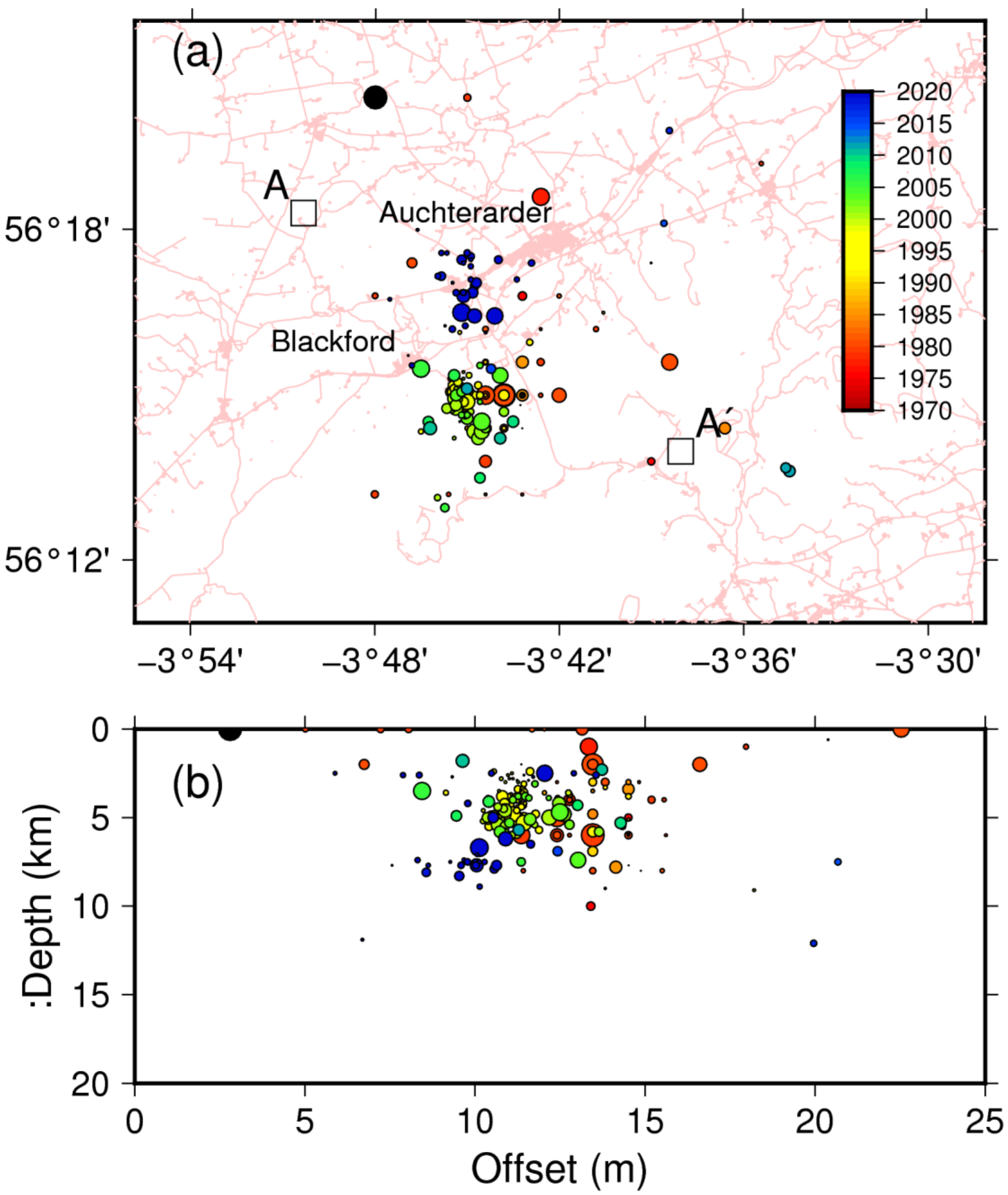


Historical (yellow circles) and instrumentally recorded earthquakes (red circles) in the vicinity of Blackford.

1977 and the end of 1980 there were nine events with magnitudes greater than 2.0 ML. The largest was on 19 February 1979 and had a magnitude of 3.2 ML. It was strongly felt, with a maximum intensity of 5 EMS and reportedly caused damage to the Glen Devon dam in the Ochil Hills. Over 191 smaller events were recorded in this 4-year period.

A total of 58 earthquakes were recorded between July 1997 and March 1998. Three of these had magnitudes greater than 2.0 ML. Between August 2000 and December 2005 a further five events with magnitudes larger than 2.0 ML were recorded. Many of these earthquakes were felt locally.

The locations for the most recent earthquakes appear to be 2 – 3km to the north of the previous events. Depths are also slightly deeper.



(a) Map of earthquakes recorded at Blackford, Perthshire. Symbols are scaled by magnitude and coloured by year. (b) Depth section between A and A´.

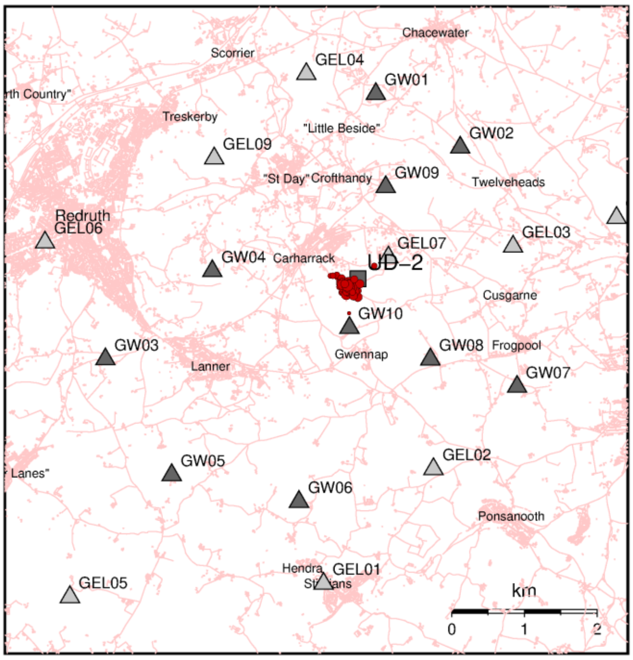
Seismicity

Induced seismicity at United Downs Deep Geothermal Project

A temporary network of ten seismic sensors was installed around the UDDGP site as part of the NERC funded Geothermal Power Generated from UK Granites (GWatt) project to help characterise fracture networks and fluid flow in the heat-producing granites.

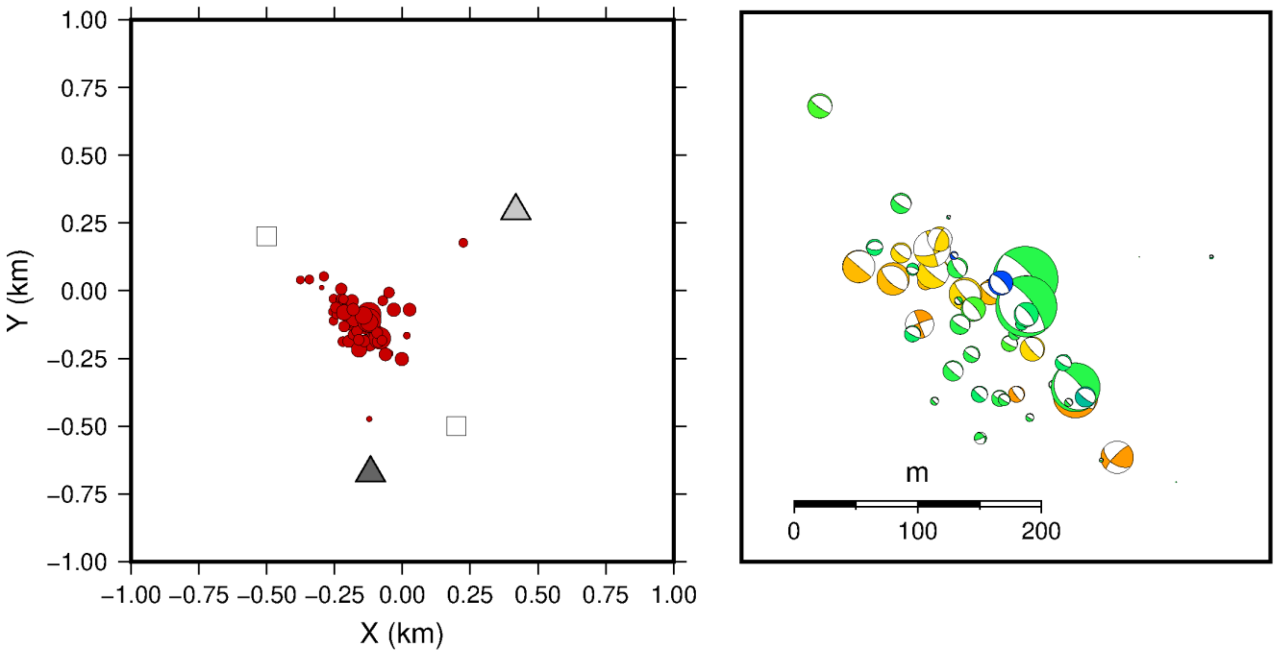
The United Downs Deep Geothermal Project (UDDGP) in Cornwall is the first geothermal power project in the UK and has the deepest and hottest onshore borehole in the UK. Over £40M has been invested in this industry-led project and it is the focus of considerable attention both in the UK and across Europe. The project is also considered important for deep geothermal to be seen as a viable renewable resource into the future. A temporary network of ten seismic sensors was installed by BGS around the UDDGP site as part of the NERC funded Geothermal Power Generated from UK Granites (GWatt) project to help characterise fracture networks and fluid flow in the heat-producing granites. The network of sensors will allow us to detect and reliably locate very small seismic events related to fluid flow as well as estimate fracture geometries. This includes understanding fluid flow paths in the granites, the relationship between seismicity and the injected fluids and potential for seismicity from this and other geothermal projects in the future.

Fluid injection tests began in late September 2020 and there has been considerable seismicity related to these, including some events felt by people in the area. Data from the temporary BGS stations have been combined with data from a local network belonging to



Seismic monitoring stations at the UDDGP. Dark grey triangles show stations installed by BGS. Light grey triangles show stations installed by the operator (GEL). The grey square shows the position of the bottom of the injection well.

Geothermal Engineering Limited (GEL), who operate the project, allowing us to detect several hundred local earthquakes with magnitudes between -1.5 ML and 1.7 ML in the time from 29 September to 1 December 2020. The events occurred at a depth of between 4.5 – 5 km, close to the point of injection. Precise relative relocation of these events shows a strong



Map (left) of epicentres for events detected during injection tests on 28 September to 1 October 2020. The events are aligned northwest-south-east. Focal mechanisms (right) for selected events predominantly show dip-slip faulting.

alignment in a northwest-southeast direction, which agrees with the strike of the nearby Porthtowan Fault. Similarly, focal mechanisms calculated for a subset of larger events also suggest dip-slip faulting along a near vertical northwest-southeast striking fault plane.

The two largest events occurred at 11:44 UTC on 30 September and 10:46 UTC on 8 December with magnitudes of 1.6 ML and 1.7 ML, respectively. The 30 September event was felt in Carharrack, Lanner, Ponsanooth and Penryn. Reports described, “felt a short rumble”, “there was a loud noise like a bang”, “the walls rattled” and “it felt like a blast at the local quarry”, indicating an intensity of around 3 EMS. The 8 December event was reported felt by a single resident in Carharrack, who described “a moderate shaking”, indicating an intensity of 2 EMS. Injection tests continued into early 2021, with further seismicity and full-scale flow tests are planned for summer 2021.

Research

Update to national seismic hazard maps

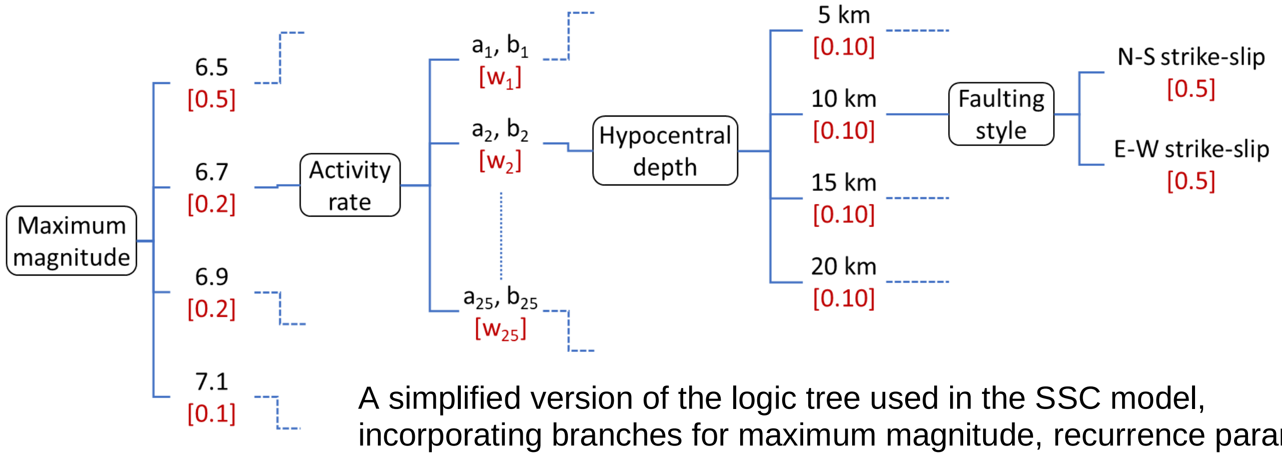
New national seismic hazard maps for the UK were published in November 2020 to update the previous maps published in 2007 and are intended to inform the National Annexes for the revised edition of Eurocode 8: Earthquake resistant design of structures.

The new seismic hazard maps are provided for three ground motion measures: peak ground acceleration (PGA) and spectral acceleration at 0.2 s and 1.0 s (assuming 5% damping) for four return periods: 95, 475, 1100 and 2475 years. These provide parameters that are directly related to those in the revision of EC8.

The hazard is calculated using Monte Carlo simulation to generate synthetic catalogues for a Seismic Source Characterisation (SSC) model. The ground motion at a given site is estimated using a Ground Motion Characterisation (GMC) model for each event in the catalogues. Uncertainties in both the SSC and GMC models are incorporated by using logic trees to account for alternative models and parameter values.

The source model consists of a series of geographic zones in which the earthquake recurrence parameters in each zone are estimated from an updated earthquake catalogue. The GMC model uses five GMPEs (ground motion prediction equations), which represent a range of tectonic environments, with host-to-target adjustments estimated for each GMPE.

PGA values for a return period of 475 years are less than 0.04 g for most of the UK, except for North Wales and the English-Wales border region where the hazard reaches around 0.09 g and 0.05 g, respectively. For the longer return period of 2475 years hazard values of 0.25 g for PGA and 0.47 g for SA0.2s are observed in North Wales. Hazard curves, uniform hazard spectra, and disaggregation analysis are calculated for selected sites in the UK located in areas of different levels of hazard. A comparison of the new hazard maps with the 2013 European Seismic Hazard Model shows a small decrease in hazard that is most apparent at a spectral period of 0.2.

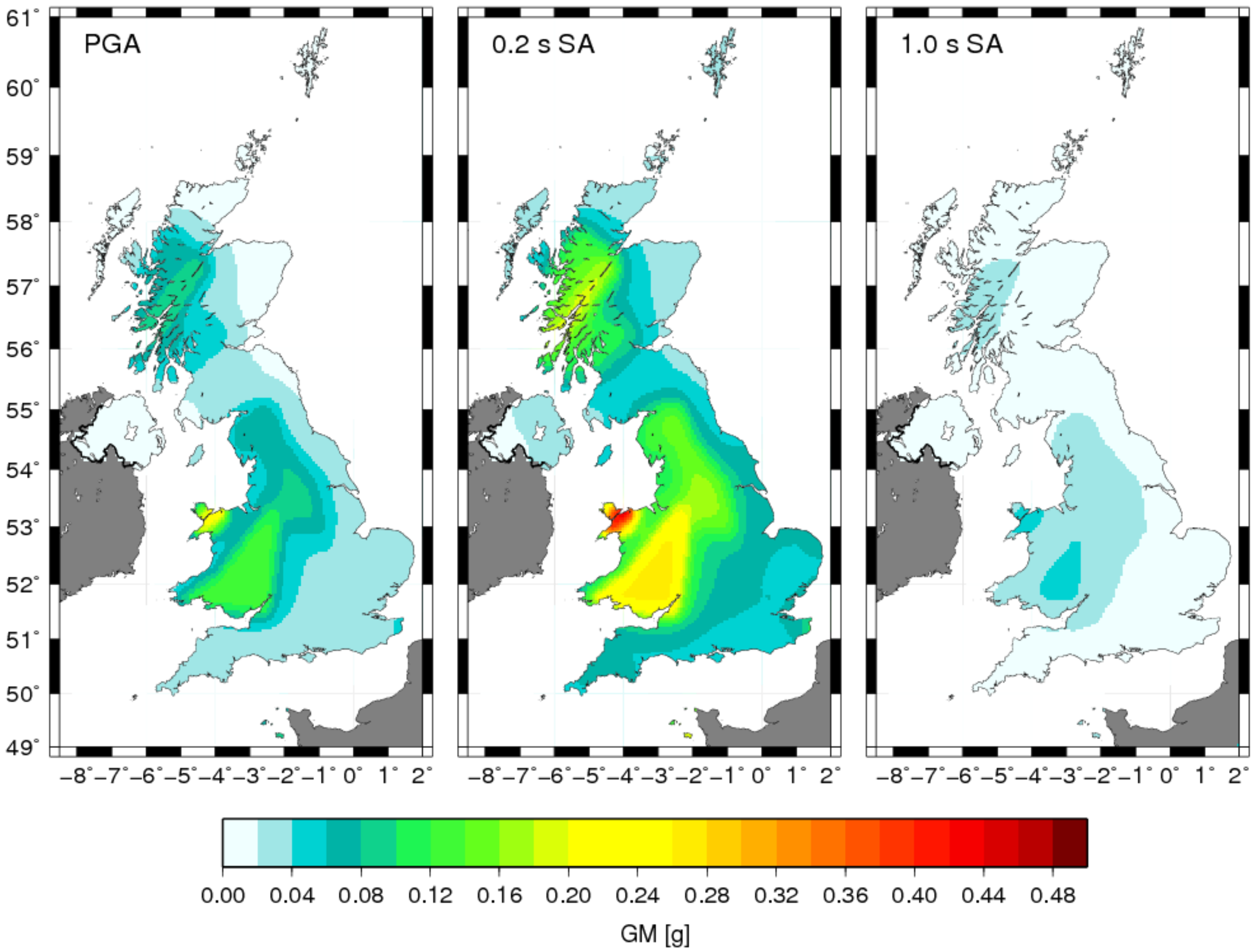


A simplified version of the logic tree used in the SSC model, incorporating branches for maximum magnitude, recurrence parameters, hypocentral depth and faulting type. Red numbers show the weight for each branch. There are 25 branches for the recurrence parameters in each zone, each containing an activity rate, a *b*-value and a weight.

The new maps enable a comparison of UK seismic hazard levels with the threshold level recommended by Eurocode8, above which consideration of seismic design becomes advisable. For most 'standard' consequence class structures, the new maps suggest that this threshold is unlikely to be crossed. However, the results will have applications for projects involving higher than 'standard' consequences of failure.

For higher consequence classes, particularly in the areas of higher-than-average seismic hazard, and for sites underlain by soft soils, some projects might need to consider whether a degree of seismic design is needed; this might apply to projects such as a large hospital providing emergency care, a vital transportation link or a manufacturing facility particularly sensitive to ground vibrations. The highest consequence class is excluded by the Eurocodes, and projects such as those in the nuclear power industry are covered by separate legislation and procedures. In these cases, there needs to be a site-specific assessment of seismic hazard extending to very long return periods, rather than the regional approach appropriate for maps. However, the extensive review of the sources of seismicity in the UK and its surroundings, and the use of up-to-date methods of assessment in the development of these maps, may still prove valuable.

This work was supported by an ICE Research and Development Enabling Fund, other seismologists and engineers based in the UK, and the British Standard Institution (BSI) sub-committee B/525/8 for Eurocode 8 (EC8): Earthquake resistant design of structures.



Hazard maps for PGA and spectral accelerations (SA) at periods of 0.2 and 1.0 seconds, for a 2475-year return period.

Research

Local site characterisation for UK seismic monitoring stations

We have used estimates of shear wave velocities and near surface attenuation at specific monitoring stations to adjust modelled ground motions for UK earthquakes and compare these with the observed ground motions.

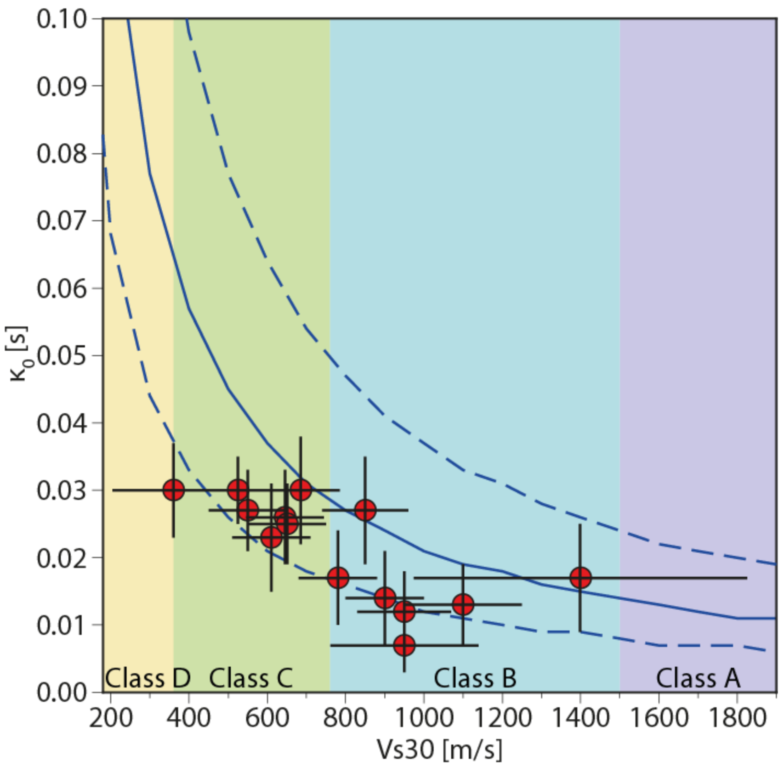
Ground motion prediction equations (GMPEs) used to estimate ground motions from earthquakes generally include terms to account for source, path and site effects. The site term accounts for differences in both elastic amplification due to shear wave velocity (Vs) structure and near-surface attenuation (κ_0, e.g., Douglas and Edwards, 2016). For most GMPEs published in the last 20 years, the elastic amplification is included explicitly, whereas the near-surface attenuation is implicitly accounted for through the data used to derive the equations.

Mosca et al. (2020) observe that many empirical GMPEs tend to under-predict the UK data when the ground motion predictions from various GMPEs are compared with the British ground motion observations. A possible reason for this is the incorrect or incomplete adjustment of the modelled ground motions to account for actual site conditions at recording sites. Another possible reason is that the modelled ground motions do not account for certain source characteristics, such as stress drops, that could result in variations in the observed ground motion.

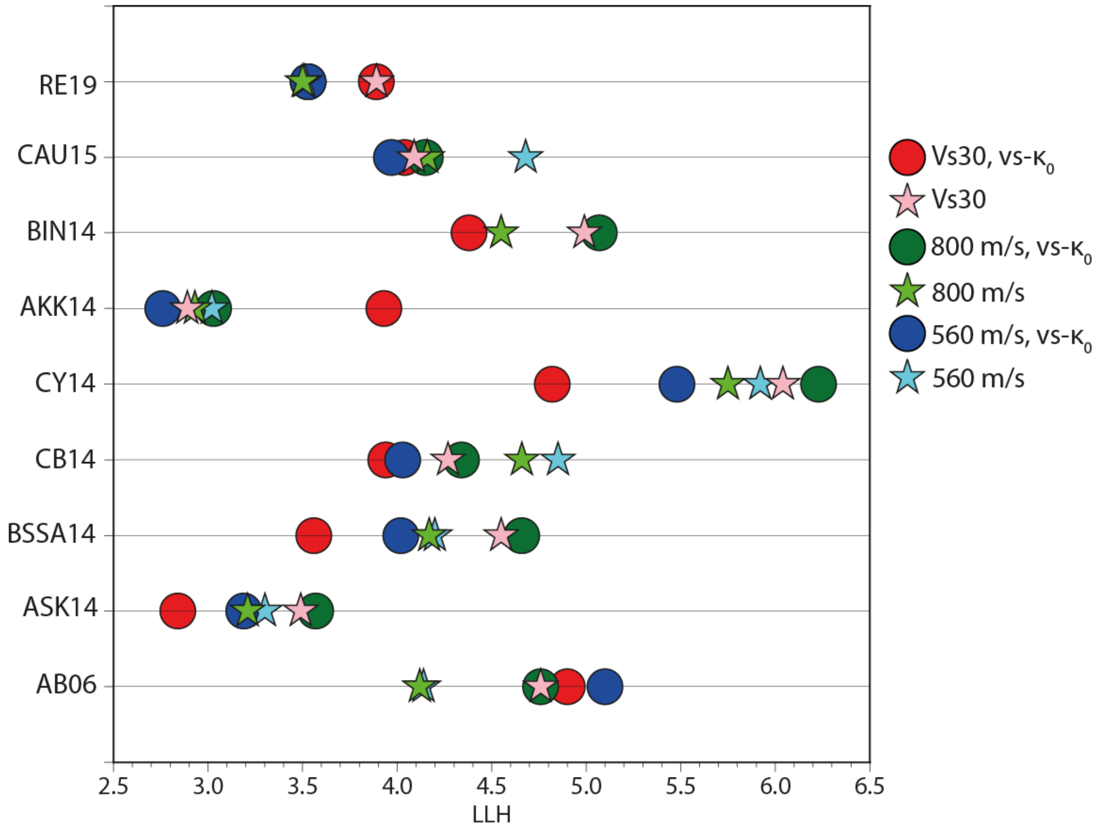
To assess the impact of site terms on modelled ground motions and account for site differences between the host and the target regions, we adjusted the ground motion modelled by selected GMPEs using estimates of local shear wave velocities and near-surface attenuation at selected UK monitoring stations. We then compared the predicted ground motions from the adjusted GMPEs with regional strong motion recordings using quantitative tests such as the log-likelihood method of Scherbaum et al. (2009).

We used Vs30 values estimated for 15 monitoring stations in the UK by Tallet-Williams (2017) using the Horizontal to Vertical Spectral ratios (HVSR) determined from recordings of ambient noise (Nakamura, 1989). The near surface attenuation parameter was estimated for the same 15 stations using the ambient noise method of Butcher et al. (2019). We then used the values of Vs30 and κ_0 for each site to adjust the ground motion predictions following the approach of Al Atik et al., (2014). This approach was also applied for the recently published national seismic hazard maps (Mosca et al., 2020), but with a generic value for each site.

Our preliminary results suggest that adjusting the modelled ground motions for Vs30 and κ_0 at each site has a relatively modest effect and the comparison between predicted and observed ground motions still shows considerable scatter. This may indicate that many empirical GMPEs are not well calibrated for the source parameters of the UK earthquakes.



Distribution of the Vs30 versus κ₀ (red circles), together with error bars, for 15 selected UK monitoring stations. The solid blue line describes the empirical relationship between Vs30 and κ0 derived by Van Houtte et al. (2011) with one standard deviation (dashed blue lines).



Likelihood scores for ground motions modelled using different GMPEs and different site terms given the observed ground motions at each site. Lower scores suggest a greater probability that the model fits the data. Red circles show the scores after adjustment using both Vs30 and κ_0 for each site. Pink stars show corrections for Vs30 only at each site. Green and blue circles show adjustments for κ0 at each site along with adjustment for Vs30 values of 800 and 560 m/s. Green and cyan stars show values with adjustments Vs30 only using values of 800 and 560 m/s at all sites.

Research

Forecasting induced seismicity due to fluid injection

New research shows how improved forecasts of induced seismicity caused by fluid injection may be possible and could be applied to mitigate risk and allow use of the Earth's subsurface as both an energy resource and for safe storage of energy.

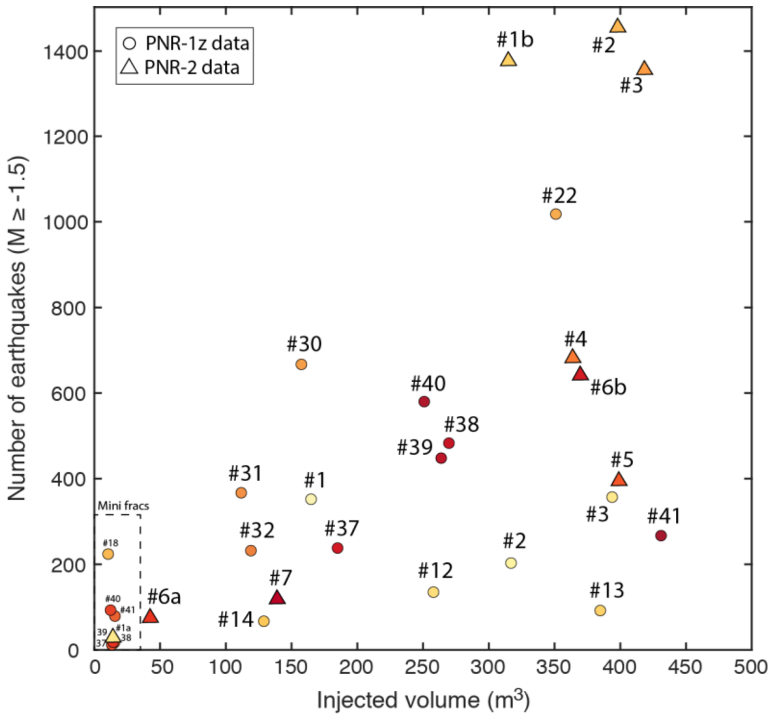
In March 2020, the Oil and Gas Authority (OGA) commissioned BGS together with researchers from the University of Bristol to investigate the efficiency of statistically forecasting the seismicity observed during and after unconventional shale gas development at the Preston New Road site near Blackpool, UK. The research used the microseismic data recorded during hydraulic fracturing operations in the PNR-1z and PNR-2 wells in 2018 and 2019, which provides a unique opportunity for fundamental research into processes leading to induced seismicity and the development of seismic risk mitigation strategies.

Mancini et al (2020) examine the relationship between the induced seismicity and the total injected volume and fluid injection rates and use this to develop statistical models of the injection-induced seismicity based on the Epidemic Type Aftershock Sequence (ETAS) models (e.g., Ogata, 1988) that are commonly used for forecasting tectonic clustered seismicity.

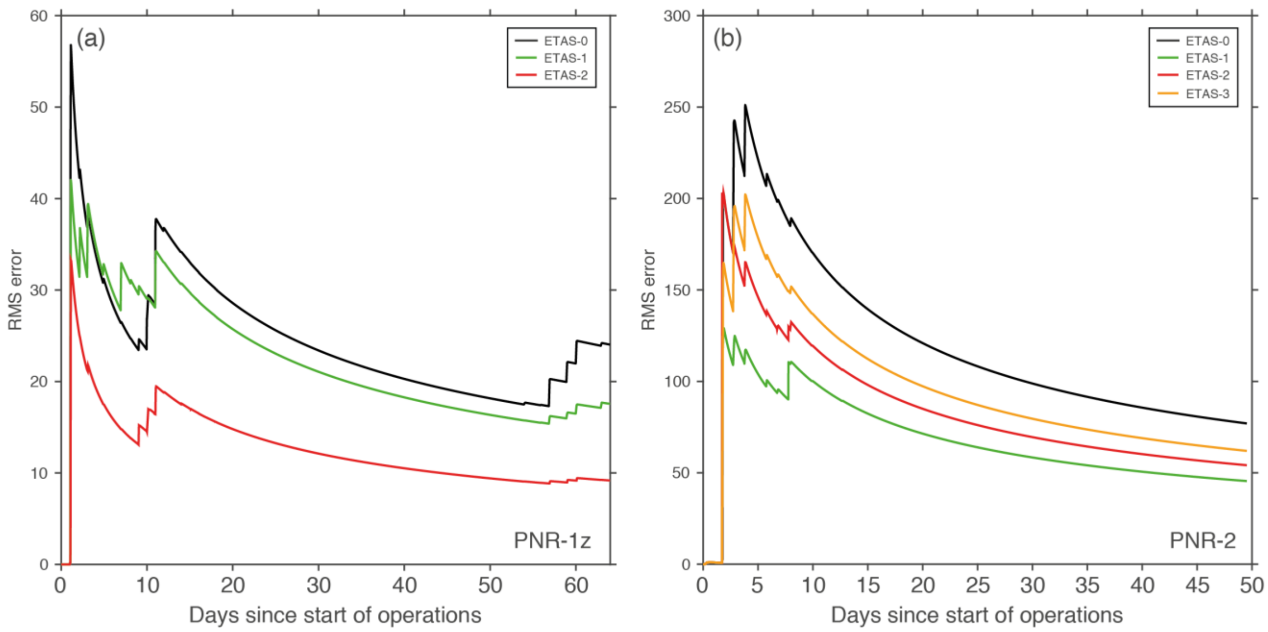
A standard ETAS model was modified by using a background seismicity rate that was proportional to the fluid injection rate to simulate the external forcing due to the pumping of pressurised fluid. Two modified models were developed using data from operations in each well. The first (ETAS-1) used an average constant of proportionality between the observed seismicity rate and the fluid injection rate for all stages. The second (ETAS-2) used a time dependent coefficient of proportionality to account for differences in the seismicity response between individual hydraulic fracturing stages.

Both the modified ETAS models provide better earthquake rate forecasts than the standard model. In particular, the ETAS-2 models best capture high seismicity rates during periods of injection. An out-of-sample forecast experiment was carried out, in which the modified ETAS model was calibrated on PNR-1z and then applied to the PNR-2 data. While the model does not perform as well as the PNR-2-specific models, its estimates are substantially more informative than the standard model, even in periods of high rates.

This provides evidence that injection-rate driven ETAS models can contribute to useful probabilistic forecasts in future induced seismicity related to fluid injection. However, this assumes that the background and injection rates are correlated, that the injection rate is known in advance and that either the well-specific average seismic response or the stage-specific seismic response is known.



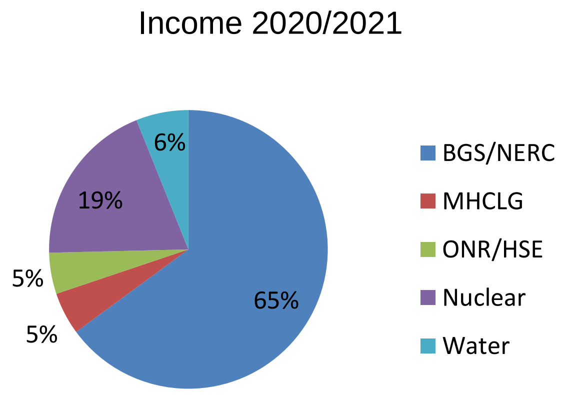
Seismicity rate (M>-1.5) during injection against injected volume by sleeve for PNR-1z (circles) and PNR-2 (triangles). Colours from yellow to red indicate increasing sleeve number (i.e., increasing time). While the seismicity rate can increase with injected volume, the relationship is complex and non-unique.

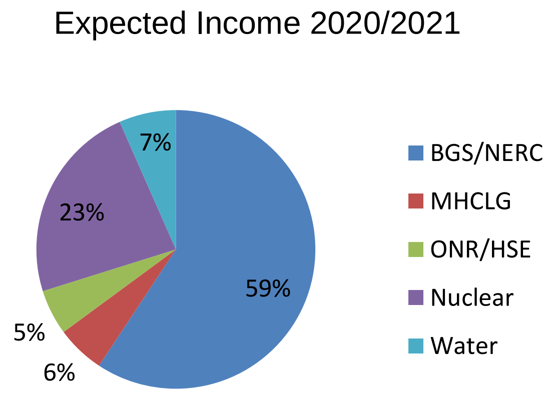


Cumulative root mean square (RMS) errors of the ETAS models as a function of time for (a) PNR-1z and (b) PNR-2. The lower the error, the better the fit between the model and the observations. ETAS-0 is the standard ETAS model for tectonic seismicity. ETAS-1 uses a coefficient of proportionality between the observed seismicity rate and the fluid injection rate that is the average of all stages. ETAS-2 uses a time dependent coefficient of proportionality. ETAS-3 applies the ETAS-2 model for PNR-1z to PNR-2.

Funding and Expenditure

In 2020-2021 the project received a total of £838K, including a contribution of £544K from NERC. Our initial NERC budget at the start of the year was £390K, but this was increased during the year with an award of £27K of funds for the repair of capital equipment along with £127K for several additional short-term projects. This was matched by a total contribution of £294K from the Customer Group drawn from industry, regulatory bodies, and central and local government.





The projected income for 2021-2022 from the Customer Group is £318K. The NERC contribution for 2021-2022 currently stands at £463K, but we hope to increase this through applications for additional funding through the year.

Acknowledgements

This work would not be possible without the continued support of the Customer Group. The current members are as follows: the Ministry for Housing Communities and Local Government, EDF Energy, Jersey Water, Magnox Ltd., the Office for Nuclear Regulation, Sellafield Ltd, Scottish Power, Scottish Water, SSE, China General Nuclear and BRBGenCo. Station operators and landowners throughout the UK have made an important contribution and the BGS technical and analysis staff have been at the sharp end of the operation. The work is supported by the Natural Environment Research Council.

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Appendix 1 The Earthquake Seismology Team

Brian Baptie	Project Manager, observational seismology, passive seismic imaging, induced seismicity.
Heiko Buxel	Installation, operation, and repair of seismic monitoring equipment.
Rob Clark	Field engineer, installation, operation, and repair of seismic monitoring equipment.
Glenn Ford	Analysis of seismic events, provision of information to stakeholders.
Davie Galloway	Analysis of seismic events, provision of information to stakeholders.
David Hawthorn	Lead engineer, installation, operation, and repair of seismic monitoring equipment.
John Laughlin	Electronics engineer, installation, operation, and repair of seismic monitoring equipment.
Richard Luckett	Observational seismology, local earthquake tomography and seismic data acquisition.
Ilaria Mosca	Seismic hazard and ground motion modelling.
Roger Musson	Honorary Research Associate, historical earthquakes, and seismic hazard.
Margarita Segou	Earthquake forecasting and improving understanding of earthquake triggering mechanisms.

Appendix 2 Publications

Baptie, B. & Reay D. (2020). Potential risks of induced seismicity from high volume hydraulic fracturing of shales in Northern Ireland. British Geological Survey Commissioned Report, OR/21/003.

Galloway, D.D. (2021). The BGS Earthquake Bulletin 2020. British Geological Survey Internal Report, OR/21/005.

Green, D.N., Luckett, R., Baptie, B. & Bowers, D. (2020). A UK local seismic magnitude scale, MLP, using P-wave amplitudes, Geophysical Journal International, 223(3), 2054–2065, https://doi.org/10.1093/gji/ggaa438.

Mancini, S., Werner, M.J., Segou, M. & Baptie, B. (2021). Probabilistic Forecasting of Hydraulic Fracturing-Induced Seismicity Using an Injection-Rate Driven ETAS Model. Seismological Research Letters, https://doi.org/10.1785/0220200454.

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White, M. Scourfield, S., Richardson, P., Baptie, B. & Gaskell, P. (2020). Induced Seismicity: Potential Likelihood and Possible Consequences. Report for Radioactive Waste Management, RWM/Contr/20/018

Appendix 3 Publication Summaries

Potential risks of induced seismicity from high volume hydraulic fracturing of shales in Northern Ireland

B. Baptie & D. Reay

Hydraulic fracturing (HF) has made it possible to economically produce hydrocarbons directly from low-permeability reservoirs such as shales by injecting high pressure fluids to create fracture networks. However, over the last decade the number of observations of induced earthquakes caused by HF operations around the world has increased as the shale gas industry has developed. Data from the US and Canada suggest that on average around 1% of HF wells can be linked to earthquakes with magnitudes of 3 or greater. Earthquakes of this size are large enough to be felt by people. However, in some areas of the US and Canada the percentage of wells associated with induced earthquakes is much higher (>30%). This variability is often explained in terms of geological factors such as proximity to existing faults. In a small number of cases, HF operations have triggered earthquakes large enough to cause potentially damaging ground motions. Such earthquakes cannot be confidently predicted in advance of operations. These observations suggest that the risk from induced seismicity during HF operations is not negligible.

Earthquakes with magnitudes greater than around 2 result from slip on existing faults that is triggered by stress changes caused by the injection of fluid during the HF process. The size of the earthquake will depend on both the area of the ruptured part of the fault and the amount of slip. Since such faults may extend outside the hydraulically fractured zone, the maximum magnitude will be controlled by local geology and tectonics, not operational parameters such as the amount of injected fluid. As a result, the maximum magnitude is highly uncertain.

Induced earthquakes have been observed in wide variety of geological settings and in areas where there are relatively few tectonic earthquakes. In some areas, the resulting hazard from induced earthquakes due to HF operations is significantly greater than the hazard from tectonic earthquakes. As a result, the low hazard from tectonic earthquakes in Northern Ireland does not guarantee that the hazard from induced seismicity will also be low.

Induced earthquakes are likely to be clustered in space and time around the locus of HF operations. Hazard is likely to increase with the number of wells and will be highest during or shortly after HF operations. Hazard may also be a function of total injected volume, with larger injected volumes leading to more earthquakes and increasing the probability of larger events. Operations that target shallow formations may pose a higher hazard, since for a given magnitude, the intensity of ground motions at the surface will be greater. The potential for actual damage depends on the intensity of motions and both the number and vulnerability of buildings exposed to ground shaking. As a result, the risk of damage to buildings will be higher in densely populated urban areas than in rural areas. Risk studies for the UK have shown that cosmetic and minor structural damage may occur for earthquakes with magnitudes as low as 3.

Higher resolution geophysical data is needed to identify fault structures and depth to basement in sedimentary basins with hydrocarbon potential in Northern Ireland in order to help mitigate risk of induced seismicity from hydraulic fracturing. Improved regional seismic monitoring should also be considered. Similarly, the present-day stress regime and stress state of faults in both the Lough Allen and Rathlin basins is poorly known. Further work is needed to address this.

Current risk-mitigation strategies have had limited success. There may be insufficient data to identify geological faults prior to operations and even where high resolution data are available, there may still be hidden faults. Similarly, traffic light systems based on specific earthquake magnitude thresholds have often failed. Statistical methods that relate the volume of injected fluid or the injection rate to induced earthquake activity may allow useful probabilistic forecasts in the future but may be associated with considerable uncertainties without calibration for local conditions.

The BGS Earthquake Bulletin 2020

D.D. Galloway

The British Geological Survey (BGS) through its National Earthquake Information Service operates a nationwide network of seismograph stations in the United Kingdom (UK). Earthquakes in the UK and coastal waters are detected within limits dependent on the distribution of seismograph stations. Location accuracy is improved in offshore areas through data exchange with neighbouring countries. This bulletin contains locations, magnitudes and phase data for all earthquakes detected and located by the BGS during 2020Maps showing seismic activity in 2020, and the larger magnitude events since 1979 (ML> 2.5) and since 1970 (ML> 3.5) are also included. The bulletin covers all of the UK land mass and its coastal waters including the North Sea (12W to 6E and 48N to 64N).

A UK local seismic magnitude scale, ML^P, using P-wave amplitudes

D.N. Green, R. Luckett, B. Baptie & D. Bowers

A local seismic magnitude scale, ML^P, has been developed for the United Kingdom (UK) using automated measurements of 8902 half peak-to-peak vertical component seismic *P*-wave displacement amplitudes from 630 earthquakes. The measurement time window increases with source-to-receiver range such that ML^P is sensitive to the dominant phase within the *P*-wave train at a given distance. To avoid contamination due to low-frequency noise, the *P*-wave amplitude measurements are made in the 1.5–30 Hz passband. A least-squares inversion was undertaken to estimate source size, distance and station effects. The distance effect values suggest that *P*-wave amplitude attenuation across the UK is low when compared to other tectonically stable regions. The station effects are broadly consistent with UK geology, with signal amplification observed within the sediments towards the south-east of the country. ML^P has been tied to the UK local magnitude scale routinely estimated by the British Geological Survey (BGS, determined using *S*-waves, and here denoted ML^{BGS}). For earthquakes with $ML^{BGS} > 3$, ML^P exhibits a closer correspondence to the moment magnitude than ML^{BGS} (i.e. $ML^P \approx M_w$). It is tentatively suggested that this reduction in bias is caused by the *P*-wave scale being less affected by along-path attenuation. The difference with respect to physical source scaling helps explain the divergence of the ML^{BGS} and ML^P scales at $ML > 3$. ML^P allows a robust estimate of event size to be made for small events which predominantly generate *P*-waves, for example, near-surface explosions. ML^P values have been calculated for 239 explosive events, mostly mining blasts and munitions disposal. Although there is significant scatter, explosive events exhibit elevated ML^P values compared to ML^{BGS}, consistent with explosions generating proportionally more compressional wave energy than earthquakes. For example, 33 explosions at sea exhibit a median ML^P–ML^{BGS} value of 0.50 mag units. Despite its sensitivity to *P*-wave amplitude, ML^P is not a more consistent estimator of explosive source size than ML^{BGS}; the magnitude residuals (station estimate − event estimate) are slightly less for ML^{BGS} compared to ML^P. This is primarily due to variability of the *P*-wave amplitudes that cannot be explained by a 1-D distance correction. ML^P should be considered as an additional tool for characterizing small seismic events within the UK.

Probabilistic Forecasting of Hydraulic Fracturing-Induced Seismicity Using an Injection-Rate Driven ETAS Model.

S. Mancini, M.J. Werner, M. Segou & B. Baptie

The development of robust forecasts of human-induced seismicity is highly desirable to mitigate the effects of disturbing or damaging earthquakes. We assess the performance of a well-established statistical model, the epidemic-type aftershock sequence (ETAS) model, with a catalog of ∼93,000 microearthquakes observed at the Preston New Road (PNR, United Kingdom) unconventional shale gas site during, and after hydraulic fracturing of the PNR-1z and PNR-2 wells. Because ETAS was developed for slower loading rate tectonic seismicity, to account for seismicity caused by pressurized fluid, we also generate three modified ETAS with background rates proportional to injection rates. We find that (1) the standard ETAS captures low seismicity between and after injections but is outperformed by the modified model during high-seismicity periods, and (2) the injection-rate driven ETAS substantially improves when the forecast is calibrated on sleeve-specific pumping data. We finally forecast out-of-sample the PNR-2 seismicity using the average response to injection observed at PNR-1z, achieving better predictive skills than the in-sample standard ETAS. The insights from this study contribute toward producing informative seismicity forecasts for real-time decision making and risk mitigation techniques during unconventional shale gas development.

National seismic hazard maps for the UK: 2020 update

I. Mosca, S. Sargeant, B. Baptie, R.M.W. Musson & T. Pharaoh

This report presents the development of the new national seismic hazard maps for the UK using a Monte Carlo-based approach. The new maps have been developed to update the advice currently given in the BSI Published Document PD6698 - Recommendations for the design of structures for earthquake resistance to BS EN 1998. The work done by the BGS team in this study has been informed at key stages by external experts who have provided advice or acted as informal reviewers (see Acknowledgements for details).

The analysis is based on a composite earthquake catalogue consisting of data from the BGS catalogue, the International Seismological Centre (ISC) online database and the earthquake catalogue of Manchuel et al. (2018) for France. A thorough assessment of the completeness of the catalogue has been undertaken. The source zone model is based on the model used by Woessner et al. (2015) for the Seismic Hazard Harmonisation in Europe (SHARE) project with some modifications. Earthquake recurrence statistics have been calculated for this model and catalogue, and the validity of the source model has been tested against the observed seismicity. The ground motion characterisation model uses the multi-GMPE model of Tromans et al. (2019) and Vs-κ_0 adjustments have been determined for these GMPEs.

The new seismic hazard maps cover the region between 49°N - 61°N and 8.5°W - 2°E and the calculations have been made at individual points spaced at 0.125° in latitude and 0.25° in longitude. The maps show peak ground acceleration (PGA) and spectral acceleration (SA) at 0.2 s and 1.0 s for 5% damping on rock (Vs30 = 800 m/s) as a proportion of g and for return periods of 95, 475, 1100 and 2475 years (these are the return periods that were requested by Panel 7 of the B/525/8 committee on Structures in Seismic Regions). Although no longer cited in the revised Eurocode 8 (EC8; CEN, 2004), including PGA in this study allows for comparison with Musson and Sargeant (2007). Uniform hazard spectra have also been calculated for four sites across the UK (Cardiff, Edinburgh, London and Dover) and a disaggregation of the hazard for these sites has also been undertaken.

For a return period of 475 years, the PGA hazard is lower than 0.04 g for much of the UK, with some exceptions: in most of Wales and North Central England, the hazard exceeds 0.04 g, reaching 0.05 g in the England-Wales border region and 0.09 g in North Wales. A similar spatial pattern in the hazard is observed at 0.2 s with the highest hazard in North Wales (0.16 g) and the variations are more pronounced. At 1.0 s, the hazard is less than 0.02 g and there is little variation across the UK.

For a return period of 1100 years, we observe a similar spatial variation with the highest hazard again in Wales (up to 0.09 g in the England-Wales border and 0.16 g around North Wales), North Central England, and western Scotland (up to 0.06 g). However, the south-eastern tip of England now shows slightly higher hazard relative to the surrounding area (up to 0.04 g). Again, this spatial variation is similar but more pronounced for 0.2 s SA where the hazard reaches a maximum of 0.29 g in North Wales. There is much less variation at 1.0 s but the England-Wales border and North Wales region are where the hazard is highest (up to 0.04 g).

For 2475 years, the Channel Islands, North Wales, the England-Wales border through to North Central England and the Lake District, and NW Scotland are the areas of highest hazard for PGA and 0.2 s SA. The highest hazard values (up to 0.25 g for PGA and 0.47 g for 0.2 s SA) are observed in North Wales.

Although this study and MS07 use different earthquake catalogues, assessments of completeness, seismic source models, and ground motion characterisation models, the two models are not markedly different and the resulting maps for PGA are similar in terms of spatial distribution of the hazard. However, there are small differences in the results. This study shows slightly higher PGA values in North Wales, North Central England, and NW Scotland, and lower PGA values around Comrie, South Wales, and Midlands than found by MS07.

The Engineering Use of the 2020 National Seismic Hazard Model for the UK

I. Mosca, S. Sargeant & B. Baptie

The Eurocode 8 (EC8) is the European Standard for the design of civil engineering projects in seismic regions. It was published in 2004 and a revision is expected in 2025. The design seismic action of a structure depends on a building classification that consists of four classes depending on the consequence of failure: CC2 for standard commercial and residential buildings; CC3 for structures whose seismic resistance has important social consequences; and CC4 for structures with the large consequence of failure. The National Annexes to the EC8 set out Nationally Determined Parameters (NPDs) that are used to estimate the elastic response spectrum, such as the maximum response acceleration at 5% damping and the acceleration thresholds for different seismicity areas. The NDPs are derived from the national seismic hazard model (NHSM).

In the United Kingdom (UK), an intraplate region with low levels of seismicity, we have recently updated the NSHM. Since the 2007 NSHM, there have been significant advances in the seismic hazard methodology, particularly with respect to how ground motion and its uncertainties are modelled. The 2020 NSHM for the UK accounts for an updated earthquake catalogue, reassessment of the catalogue analysis and the seismic source model, and advances in the ground motion modelling. The national seismic hazard maps derived from the NSHM are expressed in terms of peak ground acceleration and response acceleration at 0.2 s and 1.0 s for 5% damping on rock and various return periods. The maps confirm that seismic hazard is generally low in the UK and slightly increases in Wales and north-central England.

The 2020 NSHM and the new seismic hazard maps for the UK are used to provide the NPDs in the National Annex for the revised EC8. For most CC2 structures, the 2020 seismic hazard maps suggest that the acceleration threshold is unlikely to be crossed for a given return period. The British Standard Institution sub-committee for EC8 is evaluating whether to recommend a seismic design for CC3 and CC4 structures to the entire UK as whole or on regional basis.

Realistic microearthquake magnitudes and locations from surface monitoring of hydrofracturing at Preston New Road, UK

C. Roy, A. Nowacki, X. Zhang, A. Curtis & B. Baptie

Traffic light systems are often used to reduce the probability of damaging seismicity during anthropogenic activities such as industrial mining, geothermal energy and hydraulic fracturing operations. Under such system operations are continued (“green”), amended (“amber”) or stopped (“red”) based on the local event magnitude. Accessing accurate microseismic magnitudes is challenging due to unquantified uncertainties, which cannot be neglected in TLS because they can exceed a whole magnitude unit - large enough to make a difference between a continuation as planned (“green”) and an immediate stop (“red”) of operations. A way to account for these uncertainties in the choice of TLS thresholds was demonstrated such that an operator or regulator can choose between a system which minimizes either the risk of future larger magnitude events or the risk of incorrectly halting operations. The purpose of this study is to assess the impact of these two different TLS strategies on decision making for induced seismicity at Preston New Road, UK.

Accounting for natural uncertainty within monitoring systems for induced seismicity based on earthquake magnitudes

C. Roy, A. Nowacki, X. Zhang, A. Curtis & B. Baptie

To reduce the probability of future large earthquakes, traffic light systems (TLS) define appropriate reactions to induced seismicity depending on its local earthquake magnitude (ML). The impact of velocity uncertainties and station site effects may be greater than a whole magnitude unit of ML: this may make the difference between a decision to continue (``green'' TLS zone) and an immediate stop of operations (``red'' zone). We show how to include these uncertainties in TLS thresholds such that the risk of exceeding a threshold is minimized, or that the certainty of exceedance is maximized. We demonstrate that with the new TLS, a red-light threshold would have been encountered earlier in the hydraulic fracturing operation at Preston New Road, UK, potentially avoiding the later large magnitude events. It is critical to establish systems which permit regulators to account for uncertainties when managing risk.

Hydraulic Fracturing-Induced Seismicity

R. Schultz, R.J. Skoumal, M.R. Brudzinski, D. Eaton, B. Baptie & W. Ellsworth

Hydraulic fracturing (HF) is a technique that is used for extracting petroleum resources from impermeable host rocks. In this process, fluid injected under high pressure causes fractures to propagate. This technique has been transformative for the hydrocarbon industry, unlocking otherwise stranded resources; however, environmental concerns make HF controversial. One concern is HF-induced seismicity, since fluids driven under high pressure also have the potential to reactivate faults. Controversy has inevitably followed these HF-induced earthquakes, with economic and human losses from ground shaking at one extreme and moratoriums on resource development at the other. Here, we review the state of knowledge of this category of induced seismicity. We first cover essential background information on HF along with an overview of published induced earthquake cases to date. Expanding on this, we synthesize the common themes and interpret the origin of these commonalities, which include recurrent earthquake swarms, proximity to well bore, rapid response to stimulation, and a paucity of reported cases. Next, we discuss the unanswered questions that naturally arise from these commonalities, leading to potential research themes: consistent recognition of cases, proposed triggering mechanisms, geologically susceptible conditions, identification of operational controls, effective mitigation efforts, and science-informed regulatory management. HF-induced seismicity provides a unique opportunity to better understand and manage earthquake rupture processes; overall, understanding HF-induced earthquakes is important in order to avoid extreme reactions in either direction.

36

Induced Seismicity: Potential Likelihood and Possible Consequences

M. White, S. Scourfield, P. Richardson, B. Baptie & P. Gaskell

The UK geological disposal facility (GDF) has the potential to generate (or induce) seismicity, both through engineering activities such as construction and operation, and through the long-term evolution of the system following emplacement of the waste and engineered barrier system. Furthermore, there is a potential for human activities unrelated to the GDF to induce seismicity that could affect the construction, operation and post-closure evolution of the GDF. It is relatively well-known that human activity can result in man-made or "induced" seismicity. These events can range in magnitude from small "microseismic" events to large "earthquakes". Microseismic events are seismic events that are not felt by humans and which have a low magnitude, typically lower than 2-3 Mw. In this report, we use the term earthquakes to refer to seismic events larger than those resulting in microseismicity. Mechanisms that cause induced seismicity are associated with the introduction or removal of mass and/or heat at the surface or in the sub-surface, and the operation of chemical processes. Human developments that by their nature have the potential to induce seismicity include mining, oil and gas exploration and production (including hydraulic fracking for shale gas), water reservoir impoundment, waste water disposal, enhanced geothermal systems, use of the underground for storage, and seismic investigations of the Earth's crust. Activities in support of such developments or wider societal needs include drilling, use of explosives, use of tunnel boring machines, and use of road-headers / continuous miners.

The mechanisms through which induced seismicity might occur have been used as a basis for identifying the main ways construction and operation of the GDF might induce seismicity. These include rock drilling, blasting, operation of a tunnel boring machine, operation of a road header/continuous miner, post-excavation stress redistribution, failure of support, spalling of unsupported rock, and occurrence of a blowout / outburst. The maximum magnitude of the induced seismicity that could occur can be mitigated through good design and limited to microseismicity.

A range of GDF-induced thermal, mechanical, chemical and gas-related processes can cause fracturing and faulting of the multi-barrier system following closure of the GDF. This faulting and fracturing would generate seismicity. The magnitude and intensity of the seismicity would depend on the mode of fracturing and site-specific factors affecting propagation of seismic waves.

A features, events and processes analysis was used to identify processes that could generate seismicity during the post-closure period. For each such process, scaling laws were used to estimate the maximum potential magnitude of a seismic event that could occur as a result. Each process was classified as either a microseismic event or an earthquake event. The only processes that were judged to have potential to result in an earthquake event were:

- Higher strength rock and lower strength sedimentary rock: fracturing of the host rock and overlying rock following movement of a stack of low-heat-generating waste packages, and the resulting collapse of the backfill.
- Evaporite rock: fracture initiation and propagation in the surrounding rock in response to creep of the host rock.
- All rocks: thermoelastic effects resulting in activation of critically stressed faults.

These processes require site-specific information to understand their potential. This is particularly true for thermoelastic effects, as empirical evidence for the process comes from a region subject to significant waste water injection. The processes can be mitigated by appropriate waste acceptance criteria (e.g. specification of the maximum voidage in each package) and through appropriate backfilling approaches.

With respect to the possible consequences of seismicity induced by human actions unrelated to the GDF on GDF functionality, planning laws allow for restrictive covenants to limit human activities close to the GDF during construction and operation. Although some activities that could induce seismicity close to the GDF are considered as permitted activities and therefore would not require permit applications to proceed, planning directions could be used to limit permitted activities in a specific area. Therefore, RWM, as the developer of the GDF, does have recourse to limit the impact of seismicity induced by human actions close to the GDF (i.e. within a few kilometres from the GDF). The peak ground acceleration for human-induced seismic events several kilometres or more from the GDF would not be expected to cause damage to underground structures. Good design can optimise seismic resilience during construction, operation and closure. Post-closure consequences can be limited by the same design enhancements used to reduce the potential for the post-closure evolution of the GDF to induce seismicity.

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