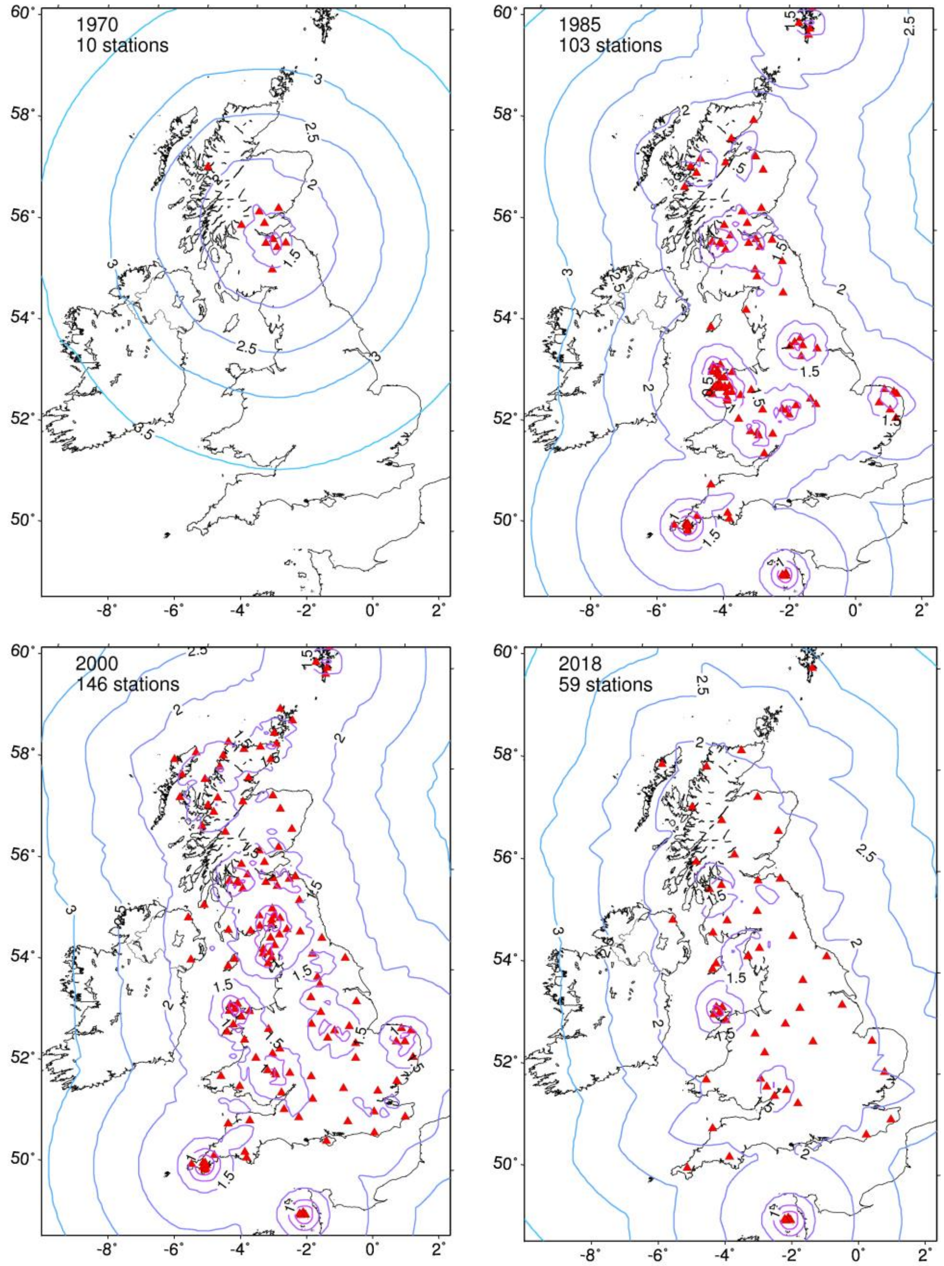
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Earthquake Seismology 2018/2019

BGS National Earthquake Information Service

Thirtieth Annual Report



BRITISH GEOLOGICAL SURVEY

OPEN REPORT OR/19/039

Earthquake Seismology 2018/2019

B. Baptie (editor)

Key words

Monitoring, Earthquakes, Seismology.

Front cover

Development of the monitoring network since the 1970's. Red triangles show operational stations. Only stations operated by BGS, as the National Earthquake Information Service (NEIS), are shown. The contours show earthquake magnitudes (ML) that can be detected. Signal amplitudes must exceed the background noise level by a factor of two at four or more stations. A noise amplitude of 10 nm is assumed for all stations.

Bibliographical reference

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Summary

The British Geological Survey (BGS) operates a network of seismometers throughout the UK in order 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).

In the 30th year of the project, we have continued to operate the national seismic monitoring network efficiently and effectively. Data from all stations were transferred directly to Edinburgh for near real-time detection and location of seismic events as well as archiving and storage of continuous data. Data latency was generally low, less than one minute most of the time, and there was a high level of completeness within our archive of continuous data.

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 were prepared and two abstracts were published in conference proceedings. This included studies of seismicity at Newdigate, Surrey and Preston New Road, Lancashire as well as a study that integrated outcomes from probabilistic and deterministic seismic hazard assessments in Central Asia. We have continued to collaborate widely with academic partners across the UK and overseas on a number of research initiatives.

A strategy document is introduced that will help to focus on the direction of the NEIS over the next 5 years, with input and feedback from Customer Group members.

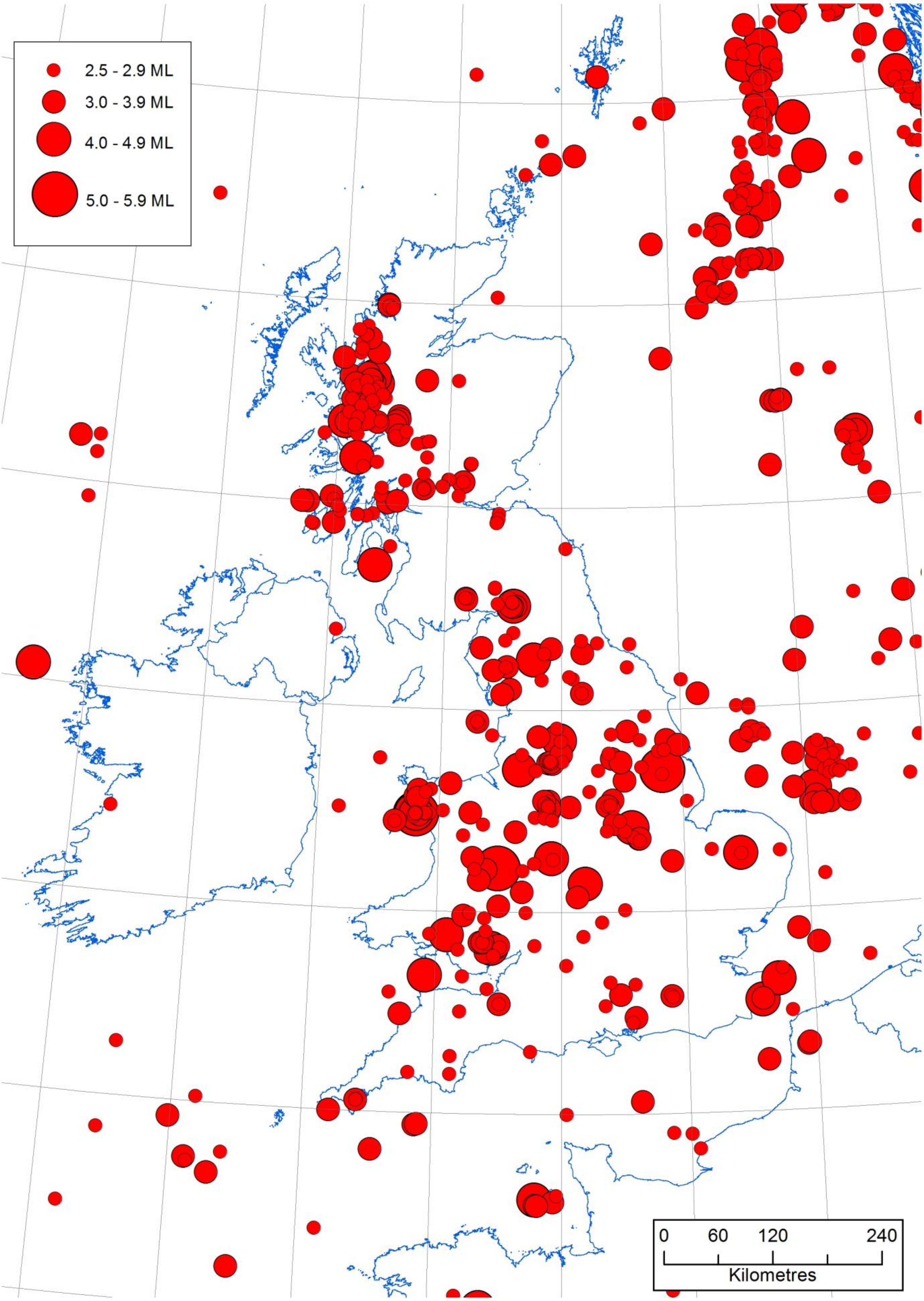
Introduction

The BGS Seismic Monitoring and Information Service has developed as a result 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 or mining-induced 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 2019.

Monitoring Network

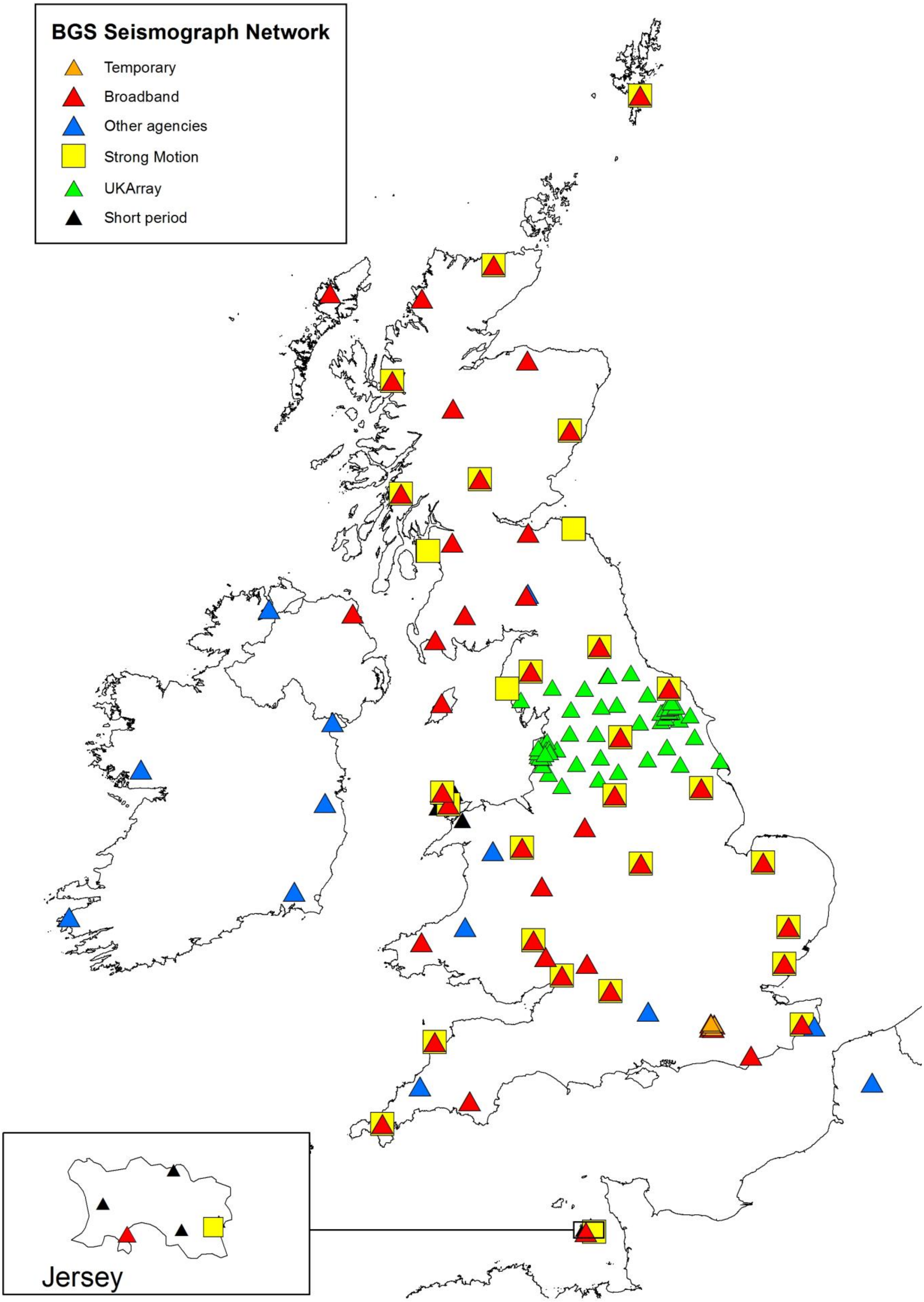
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late 1990s, the number of stations reached its peak of 146, with an average spacing of 70 km. The current network 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 in size, both in response to specific events, such as the Lleyn Peninsula earthquake in 1984, and as a result of specific initiatives, such as monitoring North Sea seismicity, reaching a peak of 146 stations by the late 1990s.

The network was divided into a number of 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 45 broadband seismometers at stations across the UK along with 33 strong motion accelerometers with high dynamic range for recording very large 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 further five temporary sensors in southeast England (all broadband) to monitor the Newdigate sequence.



BGS seismograph stations, March 2019

Achievements

Network Performance

The network contains 45 broadband sensors with 24-bit acquisition which provide real-time data from across the UK. Significant faults were rapidly identified and remedied. Data completeness is high.

The network currently consists of 45 broadband sensors, 33 strong motion sensors and 8 short period sensors. Continuous data from all stations are transmitted in real-time to Edinburgh, where they are used for analysis and archived. In the last year, all stations in the Borders short period network were decommissioned.

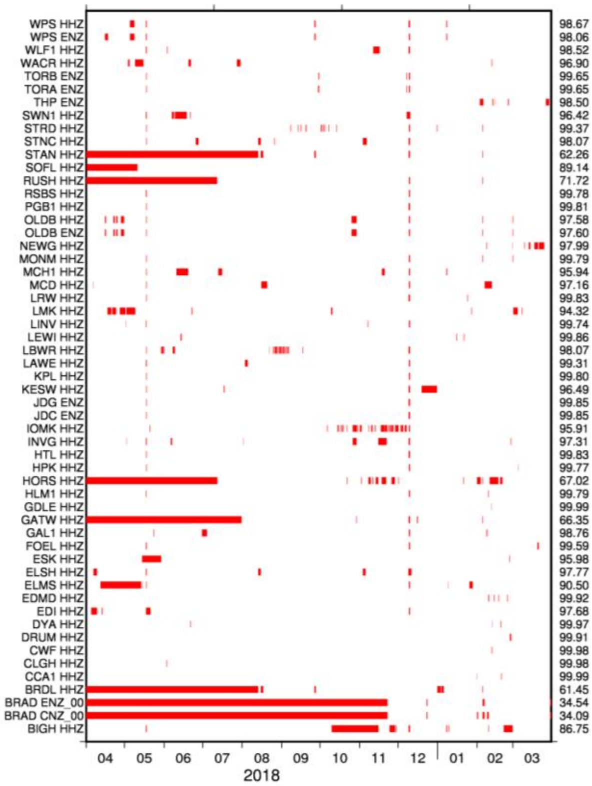
A string of borehole sensors was installed for BRB GenCo Ltd. at the Bradwell site in late 2018. The sensors include both broadband seismometers and strong motion accelerometers. BGS are managing the operation of these sensors and the data have been incorporated into our near real-time data acquisition, processing and archiving to improve our detection capability in the region.

We are continuing to use automated software processes to identify equipment faults rapidly. These identify both sudden and significant problems as well as smaller repetitive ones that over time represent a significant degradation in station performance.

In 2018/19 almost 300 separate significant faults were identified using these methods. 198 of these faults were dealt with either remotely, or with the help of a network of local contacts. 96 stations required a visit by field section staff of which 48 were permanent stations and 34 were to UKArray stations (see page 7). To improve efficiency we combine multiple site visits into a single trips, and, if appropriate, use lone working.

During the year, 157 person days were spent on fieldwork, with 87 days spent on the permanent monitoring network and 30 days on fieldwork associated with UKArray. The UKArray work included the Environmental Baseline Monitoring project in the Vale of Pickering and the Fylde Peninsula carried out for the Department for Business, Energy and Industrial Strategy (BEIS). An additional 18 days were spent on site specific monitoring and 12 days were spent on decommissioning of short period stations. 10 days of commercial work for the Dublin Institute of Advanced Studies (DIAS) were carried out installing seismometers in Iceland.

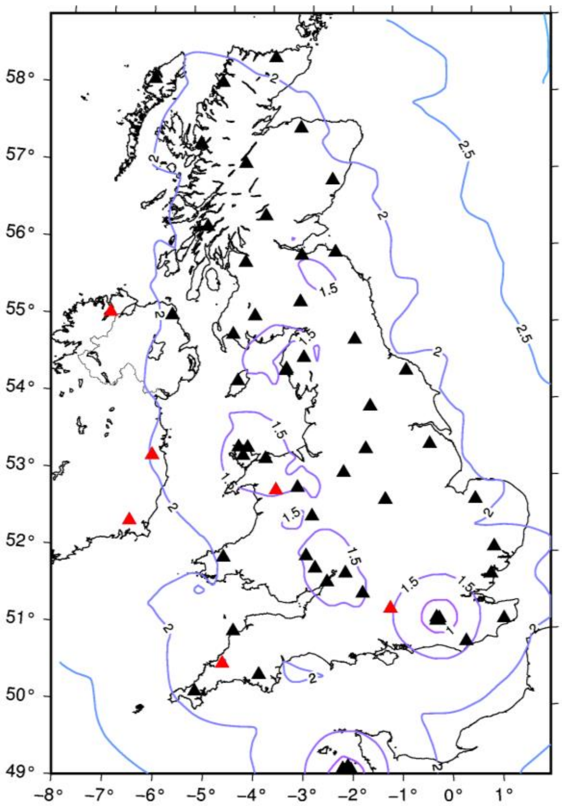
Continuous data from all our stations are archived and the completeness of these data can be easily checked to gain an accurate picture of network performance. For 2018-2019, data are more than 95% complete 92% of the time, 90% complete 96% of the time and 85% complete 100% of the time, which is a considerable improvement on the previous year when data was 85% complete for more than 93% of stations and more than 90% complete for over 89% of stations.

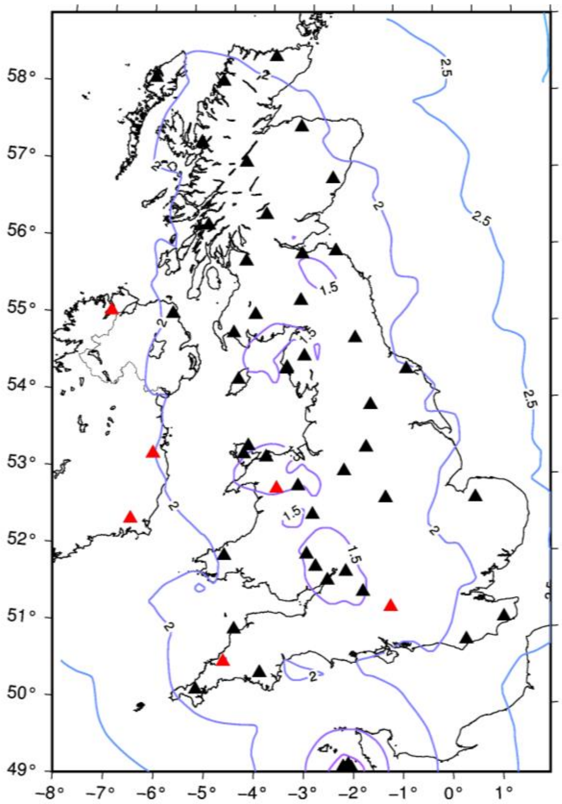


Data completeness for all broadband stations that operated throughout 2018/2019. Data are more than 95% complete 92% of the time, 90% complete 96% of the time and 85% complete 100% of the time.

The worst performing broadband stations were BIGH, Bighouse (87%), SOFL, Faroes (89%), ELMS, Elmsett (90%) and LMK, Market Rasen (94%). The stations around Newdigate, Surrey (BRDL, GATW, HORS, RUSH and STAN) and at Bradwell (BRAD) weren't operational until July and November 2018, respectively.

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, in May 2018, three stations, ELMS, LMK and WPS were down at the same time. In addition, the stations at Bradwell and Surrey, weren't operational at this time.





Detection capability of the network with (a) all stations operational (b) with ELMS, LMK and WPS 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.

Achievements

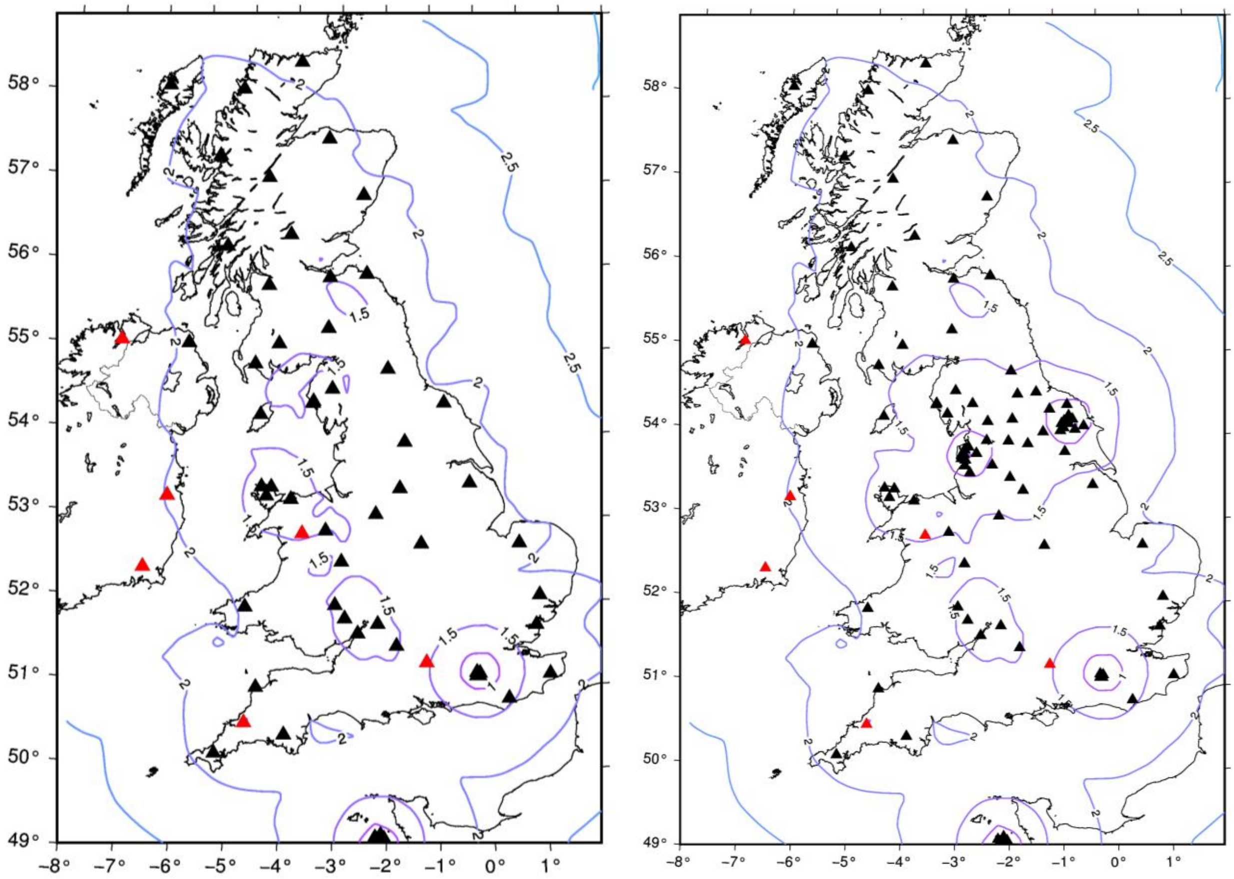
Network Development

Five temporary stations were installed near Newdigate, Surrey to study a sequence of earthquakes and provide information to assess if the events might have been induced by hydrocarbon exploration or production. Two new sensors were deployed in the north of England as part of the UKArray project.

The sequence of earthquakes near Newdigate, Surrey, in 2018/19 led to public concern that the earthquake sequence may have been triggered by nearby hydrocarbon exploration and production. The sequence included a magnitude 3.0 ML event on 5 July 2018 that was strongly felt locally. Events in April and June 2018 were located only using data recorded on the BGS network of permanent sensors. The closest permanent station to the epicentre was over 50 km away, which led to relatively large uncertainties in both epicentre and depth. Five temporary sensors were installed by BGS in mid-July close to the epicentral area. These continued to operate throughout the year and provided valuable data to improve location estimates and examine the relationship between the seismicity and local faulting in the Weald Basin. In particular, using only data from the local stations, we were able to demonstrate that the earthquake hypocentres show strong alignment along a causative fault that strikes roughly east-west and constrain focal depths at 2-2.5 km.

In 2018/2019, we installed two new UKArray temporary stations, giving a total of 36 stations across the North of England. We now consider this deployment to be complete. The array is providing high quality data for earthquakes throughout the region. For example, helping to confirm the relatively deep focus of 24 km for the magnitude 3.1 ML Newton Aycliffe earthquake on 15 September. It was also possible to determine a well constrained focal mechanism.

Continuous data from all UKArray stations are being transmitted in real-time to the BGS offices in Edinburgh and have been incorporated in the data acquisition and processing work flows used for the permanent UK network of real-time seismic stations operated by BGS. A number of detection algorithms are applied to the data in the region to detect possible events. These stations greatly improve detection capability in the north of England. They enable us to detect events with magnitude of less than 1 ML in areas of high station density.



Detection capability of the network with only permanents stations (left) and including UKArray stations (right). 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

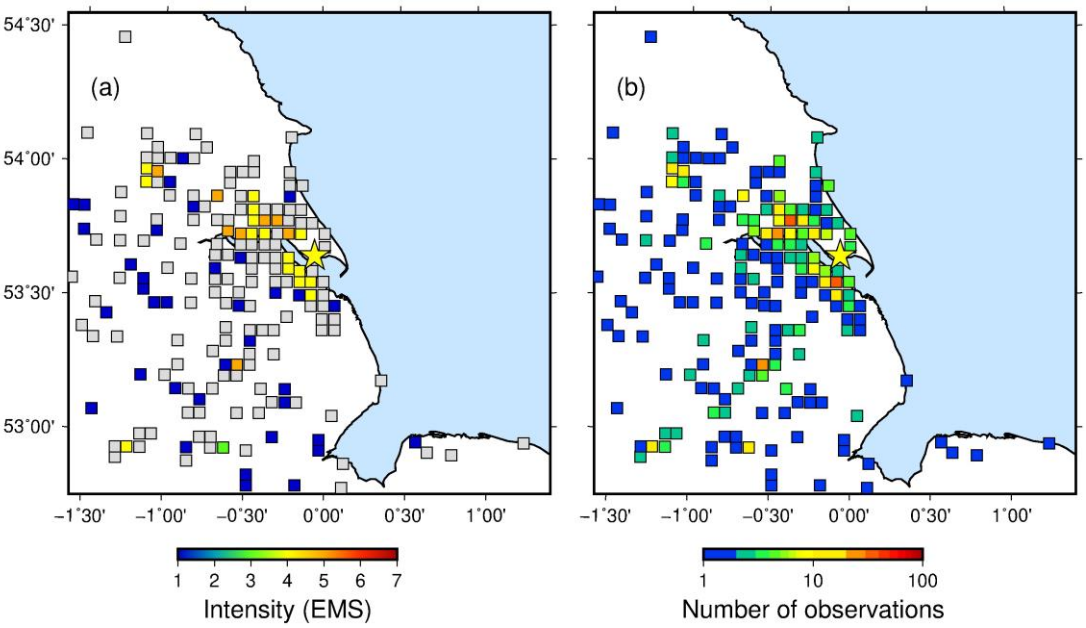
It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received alerts by e-mail whenever an event was felt or heard by more than two individuals.

Alerts were issued for 42 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-nine of the alerts were for earthquakes on mainland Britain and a further two were for earthquakes offshore in the waters around the British Isles. The one remaining alert was for a confirmed explosion in the southern North Sea on 29 August 2018.

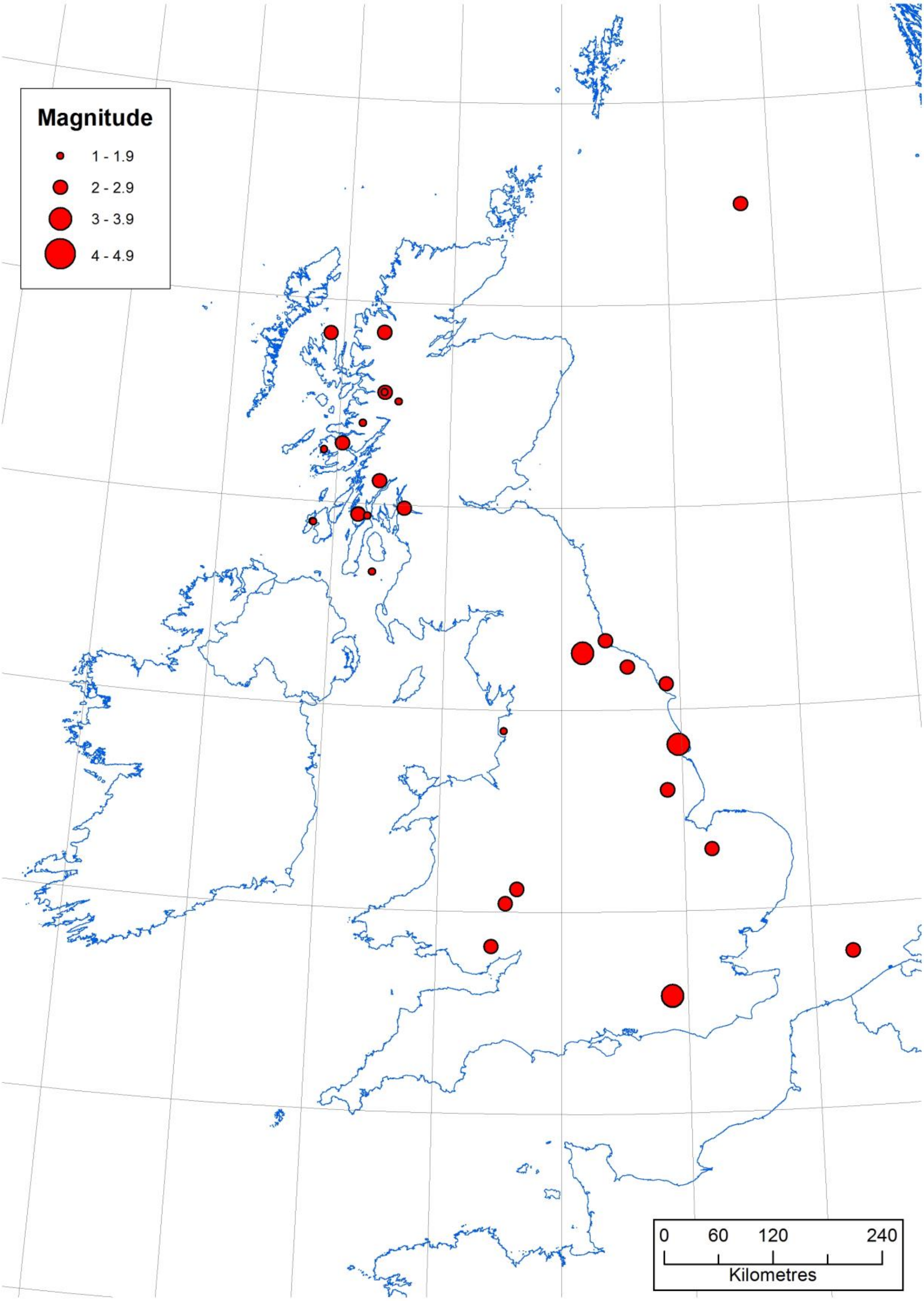
The Earthquake Seismology web pages are directly linked to our earthquake database providing near real-time lists of significant earthquake activity, together with automatically generated pages for each event.

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 that are updated in near real-time as data are contributed. We received over 600 replies following the Grimsby earthquake on 9 June 2018 (3.8 ML) and over 750 and 1600 replies following the magnitude 3.0 ML and 3.1 ML earthquakes near Newdigate, Surrey on 5 July 2018 and 27 February 2019, respectively.

Newsletters were circulated to Customer Group members for the time periods April–July, August-November and December to March. Briefing notes were issued during the induced seismicity related to hydraulic fracturing operations at Preston New Road, Lancashire.



Macroseismic intensities for the Grimsby earthquake on 9 June 2018 (yellow star). Coloured squares in (a) show intensities calculated from macroseismic data. Grey squares show places where the earthquake was felt but there were too few observations to determine an EMS Intensity. Coloured squares in (b) show the number of observations used to determine each intensity value.



Events in the reporting period (1 April 2018 – 31 March 2019) 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 schools through the UK School Seismology project and by creating dynamic web pages with background information and topical content.

David Hawthorn, Brian Baptie and Alice Walker attended the British Dam Society conference in Swansea on 13-15 September. This was a fantastic opportunity to raise awareness of BGS science and earthquake hazard in the water industry and with dam operators across the UK. The BGS stand received considerable interest throughout the meeting and all three attendees participated in a number of workshops. Several contacts were made and are being followed up. Fliers were distributed on site-specific monitoring and the Customer Group, together with information on the Swansea earthquake.

The doors of the Lyell Centre were opened on 21 September as part of Doors Open Day (http://www.doorsopendays.org.uk/). Over 500 visitors were treated to short talks as well as hands-on activities. Heiko Buxel and John Laughlin provided insights into earthquakes and their measurement, while Brian Baptie gave a presentation on Induced Earthquakes.

David Hawthorn attended New Scientist Live (https://live.newscientist.com/) at the ExCeL Centre, London on 21-23 September. The event gave the general public the opportunity to access experts in a wide range of STEM subjects, from Archaeology to Astrophysics. Over 40,000 people attended. Earthquakes and Earth hazards were a key part of the BGS display.

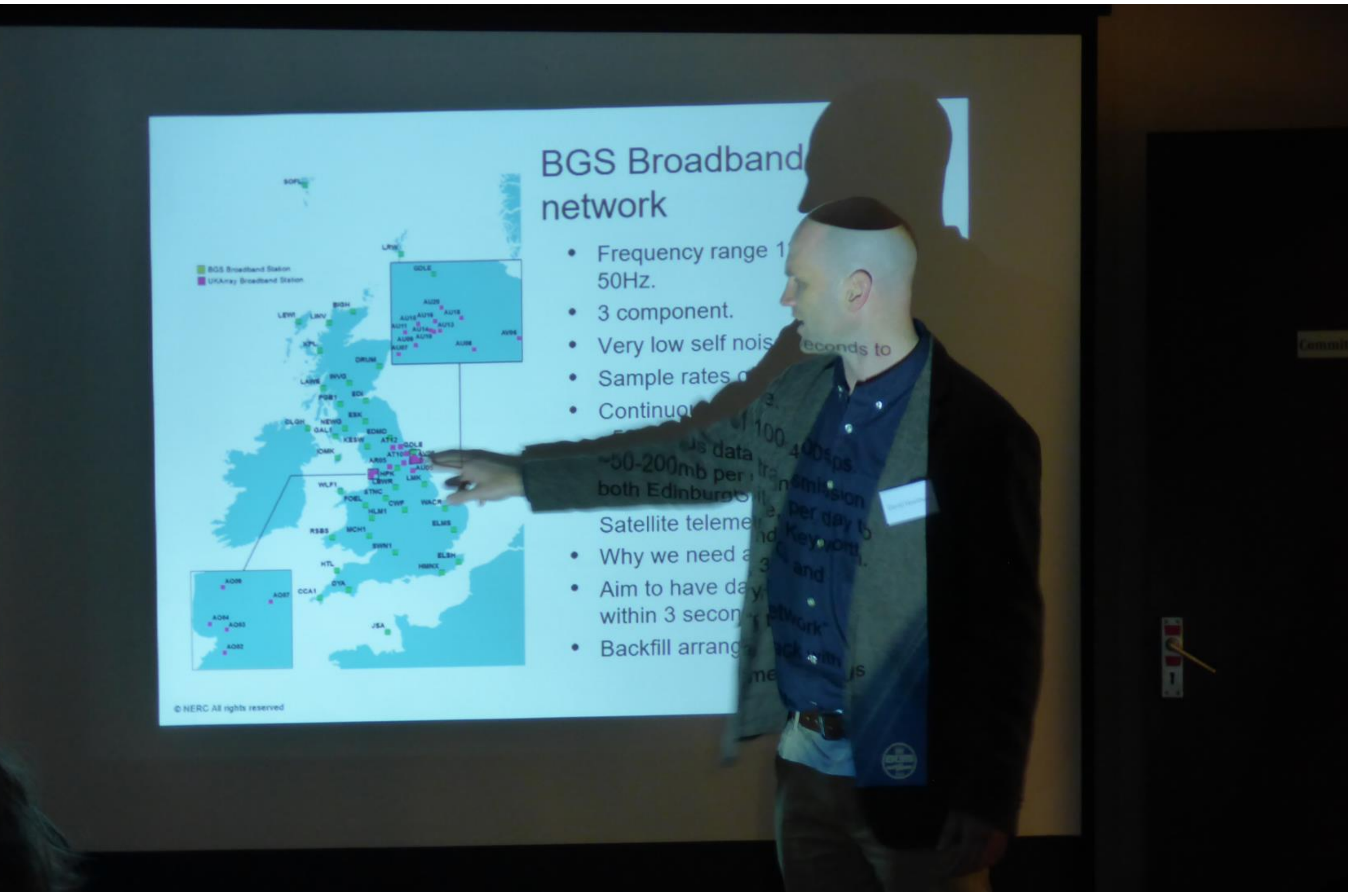
David Hawthorn also participated in a public meeting for the BGS Environmental Baseline Monitoring project in Kirby Misperton in November. The meeting was open to any member of the general public, and was also attended by the media and the local MP. David gave a short lecture outlining the seismic monitoring work being carried out in the area as part of the project.

Brian Baptie took part in a Science Media Centre (SMC) briefing on “Fracking in the UK – what does the evidence say?” on 22 January. The aim of the briefing was to talk about the science behind fracking and its regulation, and to try to separate the myths from the facts based on the best and most up-to-date evidence. The panel also included experts on groundwater and air pollution. The briefing was widely reported in the national media, particularly the conclusions that the current limit to stop hydraulic fracturing if an event with a magnitude of 0.5 ML or above occurs during operations is conservative and that this could be raised without resulting in an unreasonable increase in the risk of ground motions that may represent nuisance or cause damage. Further details can be found at http://www.sciencemediacentre.org/fracking-in-the-uk-what-does-the-evidence-say.

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 2018-2019, at least 1,328 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 240,000 visitors logged each month.

The Seismology web pages are intended to provide earthquake information to the general 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.



David Hawthorn giving a presentation at a public meeting for the Environmental Baseline Monitoring project in Kirby Misperton in November.

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.

A workshop to discuss the GMPEs to be used for the revision of UK seismic hazard maps was held in Edinburgh on 27 September. Four ground motion experts attended the meeting: Guillermo Aldama-Bustos (Jacobs), John Douglas (University of Strathclyde), Ben Edwards (University of Liverpool) and Fleur Strasser (Imperial College). From BGS, Brian Baptie, Ilaria Mosca, Roger Musson and Susanne Sargeant also attended. The aim of the meeting was to achieve a consensus view on what approach should be used. Each of the ground motion experts gave presentations on what they considered were the key issues that should be considered for the UK hazard maps and suggestions on how to proceed.

Brian Baptie has been working with researchers from the University of Bristol and Imperial College London on a new method for discriminating between natural earthquakes and those induced or triggered by human activities. This has been published in Seismological Research Letters (Verdon et al, 2019). The motivation for the work was the various investigations into the nature of the Newdigate earthquake sequence.

Ilaria Mosca has been working with Horizon Nuclear Power and Arup on a project to develop a new approach to objective quantification of the seismic source models used for seismic hazard assessment. This involves the development of a fully non-linear method to characterise seismic source zone models. The approach has been applied to the Wylfa Newydd nuclear site (Anglesey), and the results will be benchmarked against the recent PSHA developed for this site by Arup for Horizon Nuclear Power.

BGS are also participating in SERA+, a European project to improve the provision of access to data, services and research infrastructures for earthquake hazard across Europe. Ilaria Mosca attended the European Seismic Hazard Model coordination meeting, held at the 36th General Assembly of the European Seismological Commission (ESC) in September 2018 to make contact with the people who are working on the new European seismic hazard maps and highlight the BGS work on updating the UK hazard maps. Our aim is to ensure that the updated UK maps are consistent with the European maps that should be released in 2020. Ilaria also attended a ground motion workshop for the 2020 European Seismic Hazard model in Luxembourg on the 27th March 2019 and presented the approach used for the ongoing revision on the UK seismic hazard maps.

The second annual meeting for the NERC-NSF project “The Central Apennines sequence under a New Microscope” was held in Edinburgh in February. The project is led by Margarita Segou from BGS and brings together scientists from the UK (BGS, University of Edinburgh, Bristol), the US (University of Stanford, US Geological

Survey, Lamont-Doherty Observatory Columbia University) and Italy (INGV). The meeting included a dedicated workshop on induced seismicity in the US and UK to discuss improving understanding of induced seismicity.

Margarita Segou has been awarded an Honorary Fellowship from the University of Edinburgh. Margarita also visited the Istituto Nazionale di Geofisica e Vulcanologia (INGV) Rome and the Hellenic Centre for Marine Research (HCMR) to discuss ongoing research projects and possible future collaboration.

Richard Luckett and Brian Baptie are working with physicists at National Physical Laboratory on the use of submarine optical cables for earthquake detection. A paper on this work has been published in Science (Marra et al, 2018). This shows how existing telecommunication optical fibre cables can detect seismic events when combined with state-of-the-art frequency metrology techniques by using the fibre itself as the sensing element.

Brian Baptie and Richard Luckett attended a workshop on the Newdigate, Surrey earthquakes on 3 October organised by the Oil and Gas Authority (OGA), who are the regulator for onshore oil and gas exploration and production. The aims of the workshop were to present findings and discuss the nature of the earthquake activity to help inform regulatory decisions.

Brian Baptie is continuing to work with researchers from the Universities of Leeds and Edinburgh on the NERC funded REMIS (Reliable Earthquake Magnitudes for Induced Seismicity) project. The project aims to determine interlinked probability density functions of earthquake locations, magnitudes, and seismic velocities in the subsurface using a non-linear Bayesian approach.

BGS, along with the universities of Birmingham, Bristol, Manchester and York and partners from Public Health England (PHE), is continuing the independent environmental baseline monitoring programme in the Vale of Pickering, North Yorkshire. This project is funded by BEIS.

BGS continues to exchange data with other agencies to help improve source parameters for regional and global earthquakes. Phase data are distributed to the (EMSC) to assist with relocation of regional earthquakes and rapid determination of source parameters. Phase data for global earthquakes are sent to both the National Earthquake Information Centre (NEIC) at the USGS and the International Seismological Centre (ISC). This year, data from 457 seismic events were sent. Data from the BGS broadband stations are transmitted to both ORFEUS, the regional data centre for broadband data, and IRIS (Incorporated Research in Seismology), the leading global data centre for waveform data, in near real-time.

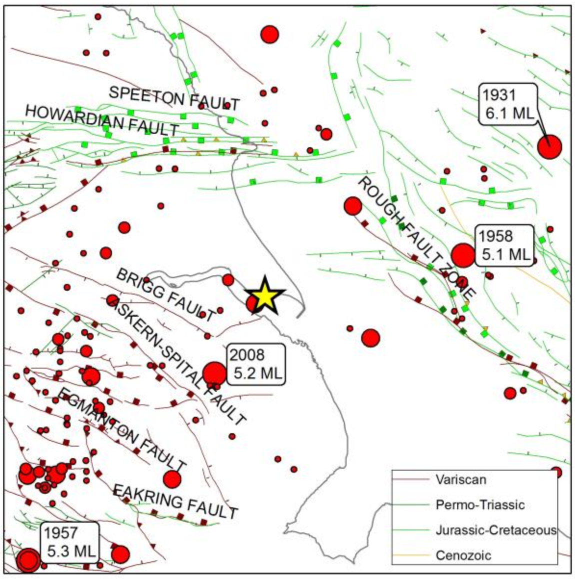
Seismic Activity

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.

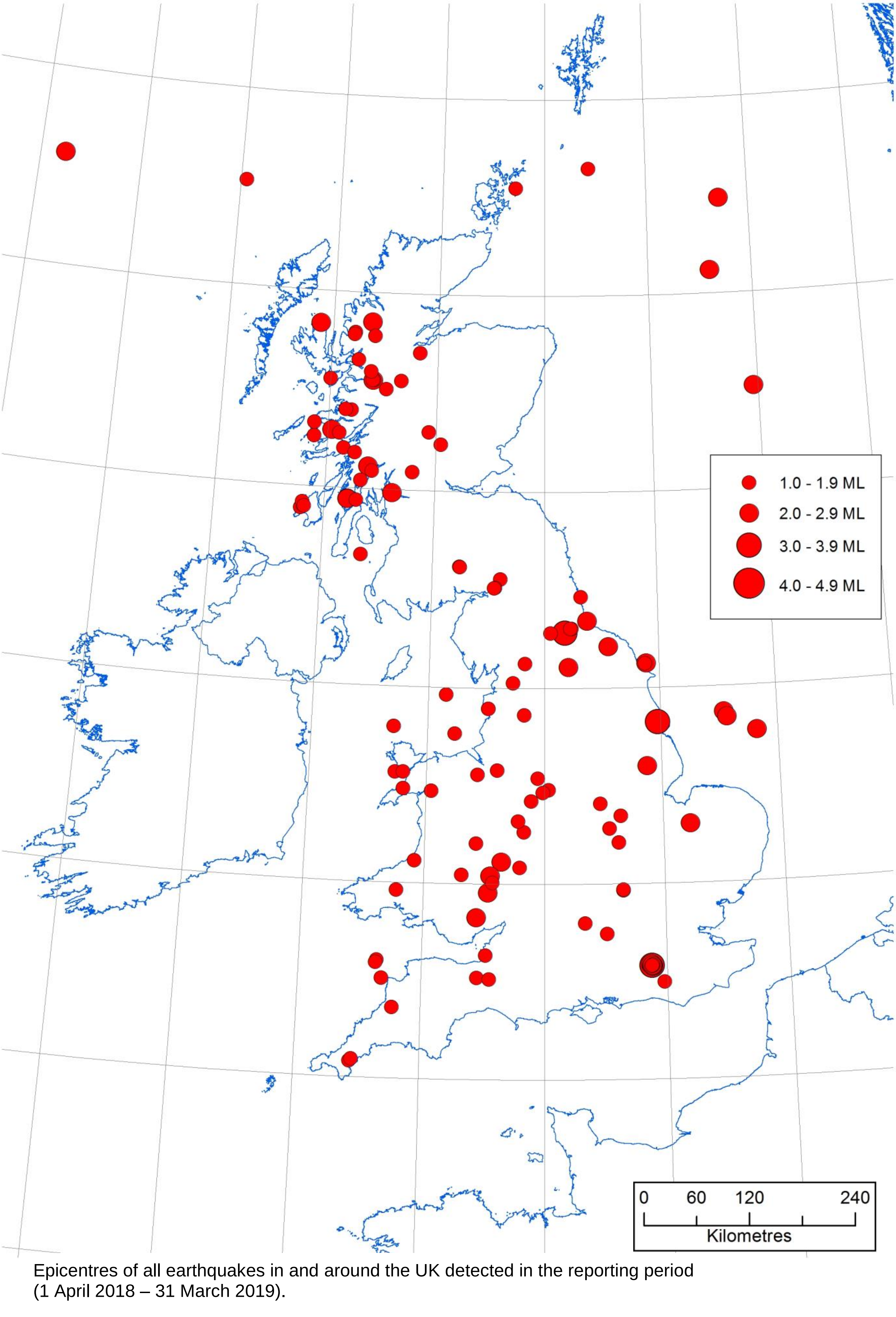
There were 284 local earthquakes located by the monitoring network during 2018-2019. Thirty-seven of these had magnitudes of 2.0 ML or greater and five had magnitudes of 3.0 ML or greater. Seventeen events, with a magnitude of 2.0 ML or greater, were reported felt, together with a further 14 smaller ones, bringing the total to 31 felt earthquakes in 2018-2019.

A magnitude 3.8 ML earthquake occurred approximately 10 km north of Grimsby, East Lincolnshire, on 9 June. We received over 600 reports of the earthquake being felt, most of them from people living in nearby Grimsby and Hull. Intensities of 4 EMS were observed in Grimsby and 5 EMS in Hull, indicating moderate to strong shaking. Typical reports described shaking lasting for a few seconds with doors and windows rattling. It was the largest earthquake in the region since the magnitude 5.2 ML earthquake near Market Rasen on 27 February 2008. The location was very close to the magnitude 4.2 ML event in 1703 that caused some minor damage in Hull. The largest known British earthquake, a magnitude 6.1 ML in 1931, occurred approximately 100 km to the east in the North Sea. The recent deployment of UKArray stations to the north and west meant the event was well recorded and a well constrained focal mechanism shows strike slip faulting on fault planes that strike either NNE-SSW or ESE-WNW.

A magnitude 3.1 ML earthquake was recorded near Newton Aycliffe on 15 September. This earthquake occurred in an area where there has been little other recorded seismicity and it is the largest earthquake in this part of the UK since a magnitude 3.6 ML earthquake near Ripon in 2011. We received no reports of the earthquake being felt, perhaps because of the relatively deep focus of 24 km. The recent deployment of UKArray stations to the north and west meant the event was well recorded and a well constrained focal mechanism shows strike slip faulting on fault planes that strike either NNE-SSW or ESE-WNW.



Historical and instrumentally recorded earthquakes (red circles) in the region of the magnitude 3.8 ML Grimsby earthquake on 9 June 2018 (yellow star). Lines show mapped faults coloured by age.



Epicentres of all earthquakes in and around the UK detected in the reporting period
(1 April 2018 – 31 March 2019).

Seismic Activity

Newdigate, Surrey

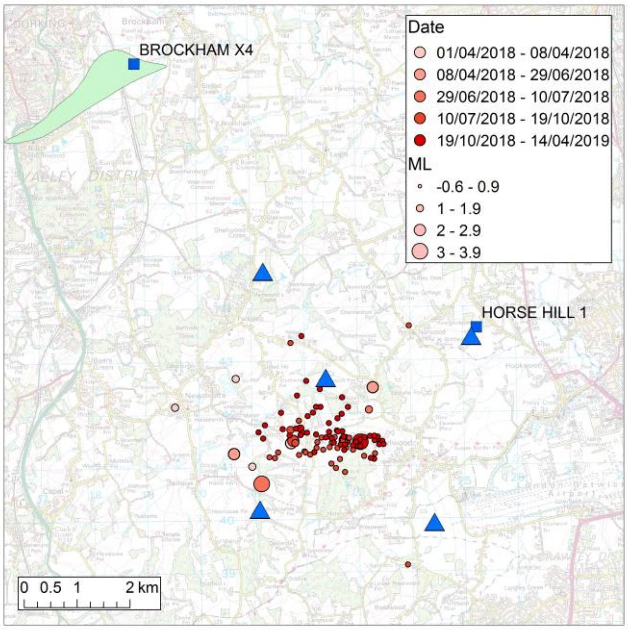
A sequence of small earthquakes started near Newdigate, Surrey, on 1 April 2018. Nine earthquakes with magnitudes of greater than 2.0 ML were recorded over the next year. The largest was on 27 February 2019, with a magnitude of 3.1 ML. The activity led to much public concern that the earthquake sequence may have been triggered by nearby hydrocarbon exploration and production.

The sequence started with a magnitude 2.6 ML event on 1 April 2018. Five other earthquakes with magnitudes of greater than 2.0 ML were recorded in 2018. The largest was on 5 July 2018, with a magnitude of 3.0 ML. It was preceded by two events with magnitudes of 2.6 and 2.4 ML on 27 and 29 June, then followed by seven aftershocks, the largest of which had a magnitude of 2.4 ML. Seven of the earthquakes in 2018 were felt by people living nearby, leading to public concern that the earthquake sequence was triggered by nearby hydrocarbon exploration and production.

Five temporary sensors were installed by BGS in mid-July close to the epicentral area to study the events in more detail.

Further earthquakes with magnitudes of 2.4 and 2.0 ML were recorded on 14 and 19 February 2019, respectively. Both were felt by people nearby. These were followed by a magnitude 3.1 ML earthquake on 27 February, which was strongly felt locally.

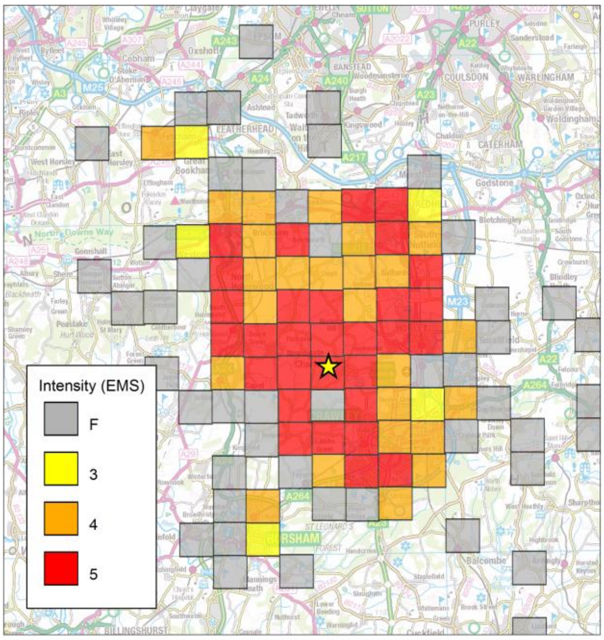
Our analysis shows that earthquake epicentres are tightly clustered in a small source zone that lies between the villages of Newdigate and Charlwood, and at a distance of approximately 8 km from the Brockham oil field and approximately 3 km from the Horse Hill 1 well (HH-1). The locations for events that occurred after the temporary sensors were deployed in mid-July are the best constrained and show



Seismicity near Newdigate, Surrey. Events are scaled by magnitude and coloured by date, with the most recent events coloured dark red. Blue triangles show the locations of the temporary stations installed by BGS.

some alignment in an EW direction, just west of Charlwood, which is in good agreement with the mapped EW faults that run through the region. Depths calculated using only local recordings suggest that the events are most likely to have occurred at depths of approximately 2 km.

BGS received over 1,600 reports from members of the public who felt the magnitude 3.1 ML earthquake on 27 February and these data were used to determine the strength of shaking in terms of macroseimic intensities. We find that

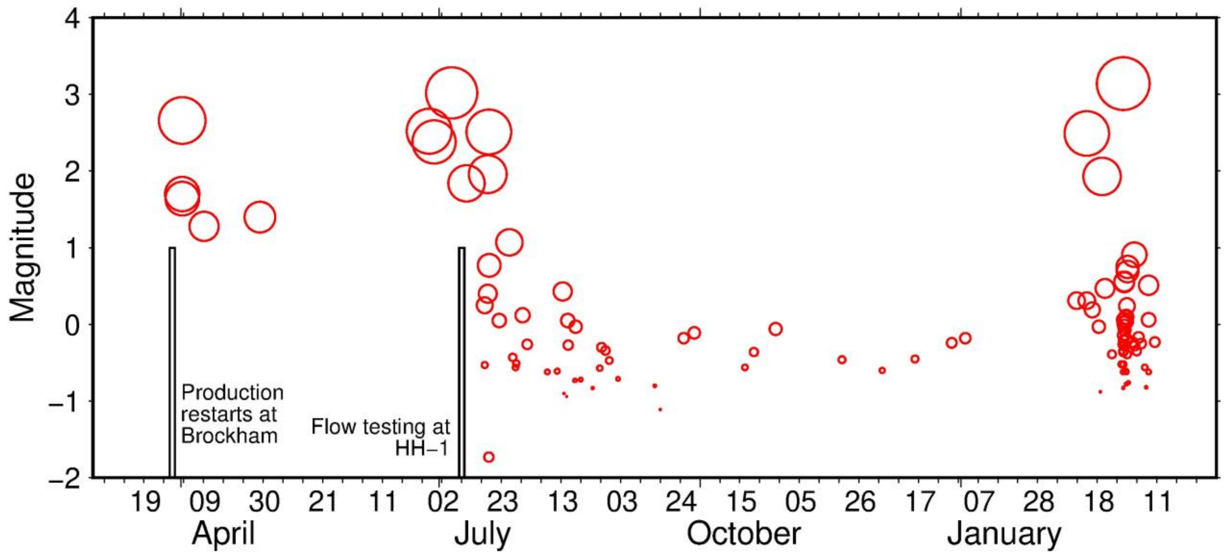


Macroseismic intensity for the magnitude 3.1 ML earthquake on 27 February. The yellow star shows the epicenter. Intensities are calculated in 2 km grid squares from over 1600 reports from people who felt the earthquake. A minimum of five observations is needed in any grid square to calculate a value of intensity, otherwise the value is recorded as “Felt”, but no intensity is calculated.

intensities of 4-5 EMS were observed at distances of up to 10 km from the epicenter, but the event does not appear to have been felt beyond this, which is consistent with the shallow hypocenter.

Oil production at the nearby Brockham field resumed on 23 March 2018 after a two year hiatus. Information provided to the Oil and Gas Authority (OGA) by the operator of the HH-1 well states that flow testing started on 9 July 2018, however, the earthquake sequence was already underway at this point. Production at both Brockham and HH-1 is from the Portland sandstone at a depth of approximately 600 m.

A detailed report (Baptie and Luckett, 2018) on the earthquake sequence was written for an Oil and Gas Authority (OGA) workshop that was held on 3 October 2018. We used the criteria suggested by Davis and Frohlich (1993) to assess the available evidence that the earthquake sequence may have been induced. This suggests that the events are unlikely to have been induced.



Earthquake activity as a function of time showing the evolution of the sequence. Circles are scale by magnitude.

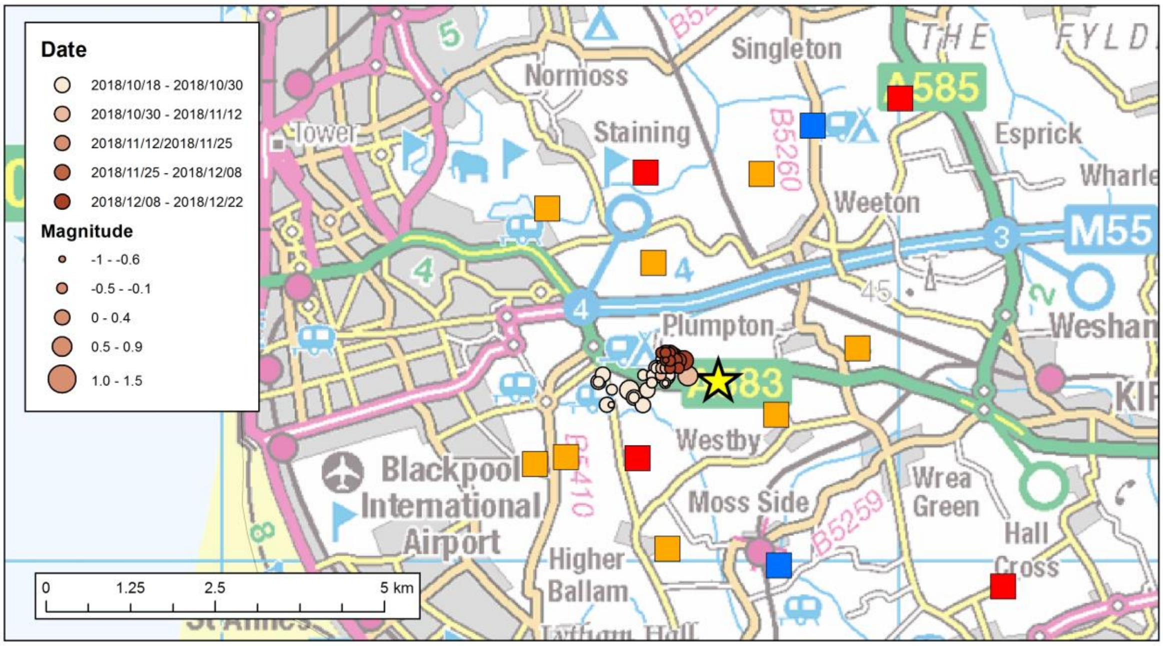
Seismic Activity

Preston New Road

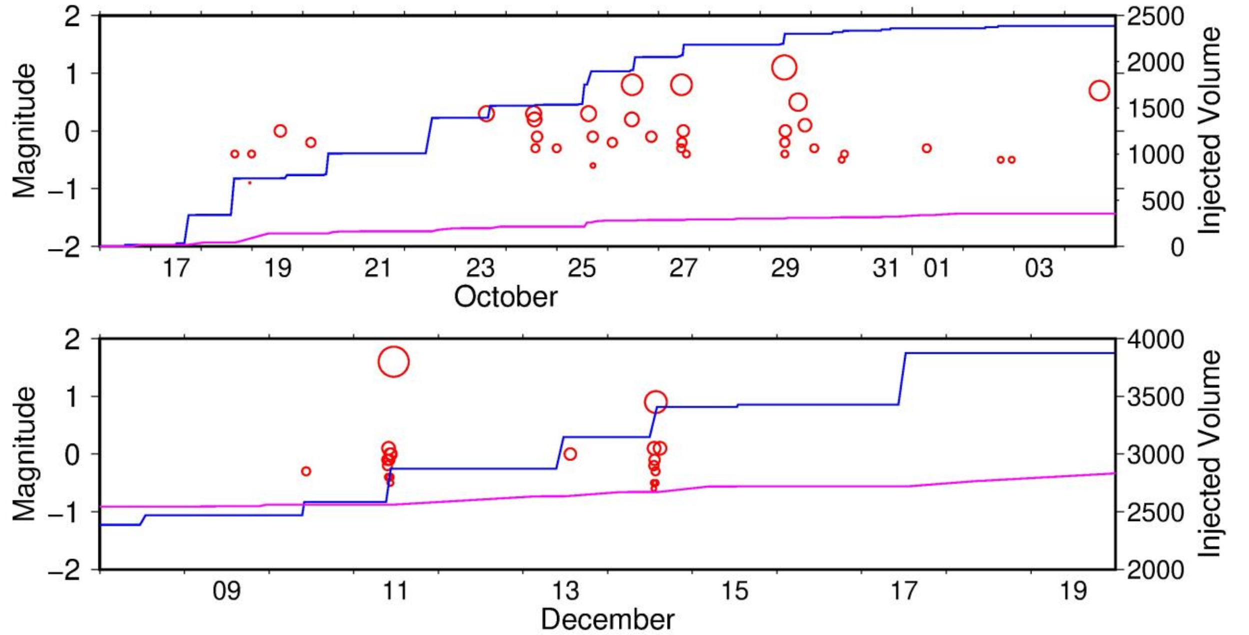
Hydraulic fracturing of an unconventional shale gas reservoir in northwest England began in October 2018, over seven years after induced seismicity related to the first such operations in the UK resulted in a moratorium. The detected seismicity is strongly clustered in space and time and associated with periods of injection.

Hydraulic fracturing of the Bowland Shale at Preston New Road, Lancashire, began in October 2018, over seven years after induced seismicity related to the first such operations in the UK resulted in a moratorium. A network of surface sensors had been installed by BGS between 2015 and 2017 to monitor background earthquake activity and any induced seismicity. We also received data from Cuadrilla Resources from a network of stations installed in order to comply with regulatory requirements. This dense network allowed us to detect much smaller earthquakes than we are typically able to do in other parts of the UK.

Hydraulic fracturing was carried out in a number of stages over a 700 m interval of the PNR-1 horizontal well at a depth of approximately 2,300 m. The detected seismicity is strongly clustered in space and time, associated with known periods of injection, with only small numbers of “trailing” events. Similarly, the seismicity is also observed to migrate from west to east, again, corresponding to the spatial locations of different stages of hydraulic fracturing.

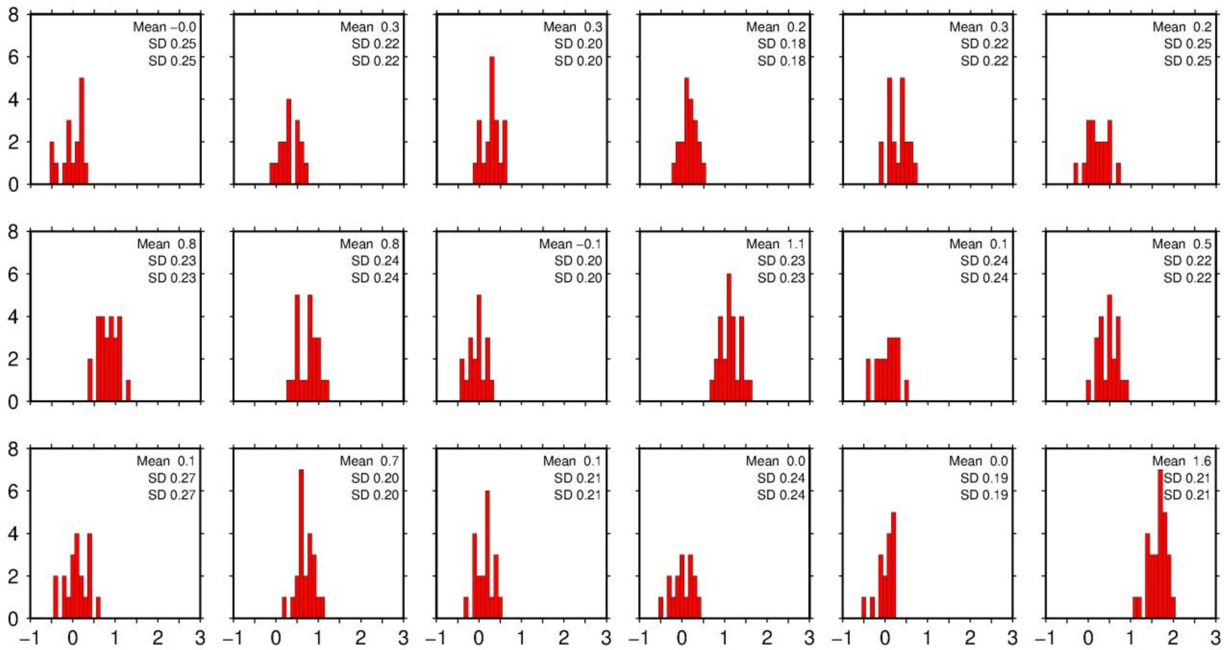


Circles show earthquakes detected by the surface seismic monitoring network during operations. The circles are coloured by date and scaled by magnitude. Squares show the locations of sensors installed by BGS (red), Cuadrilla Resources (orange) and Liverpool University (blue). The star shows the surface position of the PNR-1 well.



Observed seismicity as a function of time and magnitude (circles). Circles are scaled by magnitude. The blue line shows the cumulative injected volume. The magenta line show the flowback volume.

The hydraulic fracture plan (HFP) allowed for injected volumes of up to 765 m^3 per stage. As a result, the levels of seismicity were low, but despite this, a number of events exceeded the magnitude limit of 0.5 ML that is set by current regulations and requires operators to temporarily stop injection. The largest event detected had a magnitude of 1.5 ML and occurred at 11:21 UTC on 11 December. It was around 60 times smaller than the magnitude 2.3 ML event that stopped hydraulic fracturing operations at Preese Hall in 2011, resulting in the moratorium. Magnitude measurements at individual stations show considerable variance, with standard deviations for events with magnitudes of greater than 0 ML showing standard deviations of as high as ±0.27 ML. The range in station magnitudes often exceeds one magnitude unit. This highlights one of the problems in the reliable characterisation of induced seismicity during operations using surface arrays.



Histograms showing local magnitudes calculated at each station for events with ML > 0.

Research

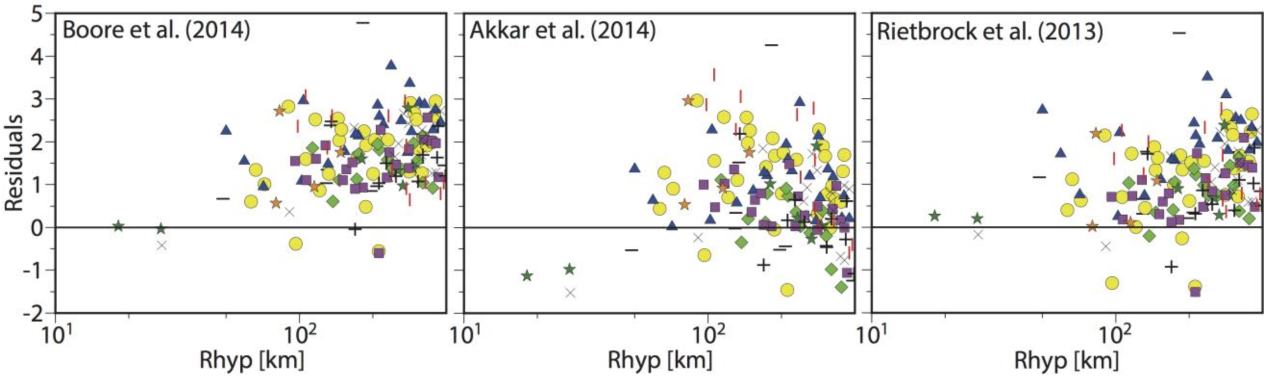
Revising the Seismic Hazard Maps for the UK

The UK national seismic hazard map (Musson and Sargeant, 2007) is over 10 years old, and requires an update to inform the UK's revised National Annex to the 2020 version of Eurocode 8. Following discussions with the BSI National Committee B/525/08 (Structures in Seismic Regions) and the wider UK engineering community, BGS has started a project to update the hazard maps.

The last seismic hazard maps for the UK were produced by Musson and Sargeant in 2007. Since then, significant advances in probabilistic seismic hazard assessment methodology have been made, particularly in the way that ground motion is characterised. As a result, there is a strong argument for revising the seismic hazard maps for the UK.

Our approach has been developed in consultation with the potential users of the map and experts in seismic hazard assessment from outside the project team. Engineers from the B/525/08 committee on Structures in Seismic Regions (the committee responsible for UK input to Eurocode 8) provided guidance on the design requirements for the seismic hazard maps so that they could be used in the revised UK National Annex associated with the 2020 revision of Eurocode 8.

The new maps are currently being developed using a modified version of the source model used in the SHARE (Seismic Hazard Harmonization in Europe) project and an updated earthquake catalogue. However, the main difference between this work and that of Musson and Sargeant (2007) is how ground motion, and its uncertainty, are modelled. The aim of the current work was to develop a ground motion model in a way that reflects current



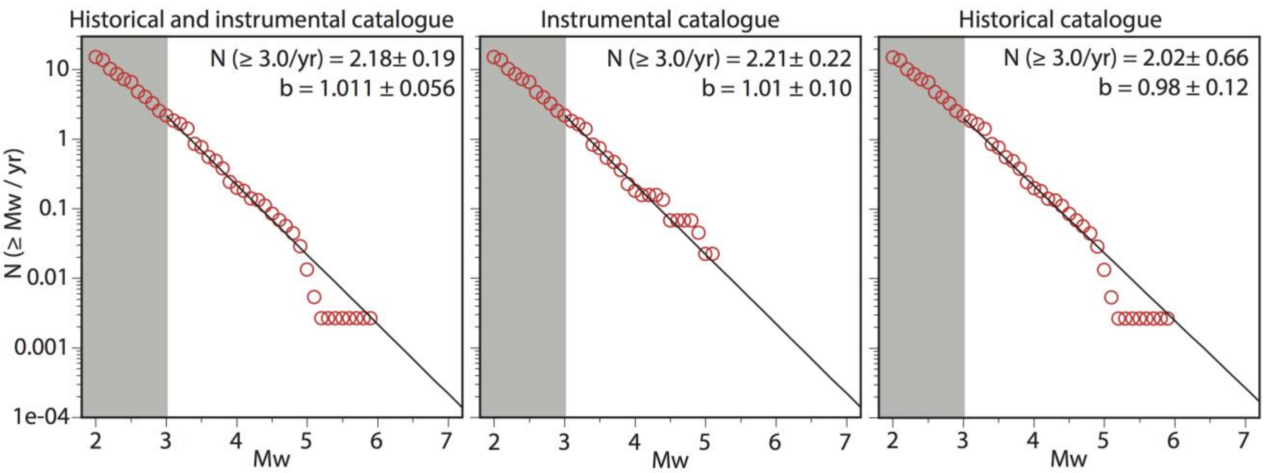
Residuals between observed ground motions for selected UK earthquakes and the predictions from three GMPEs. Different symbols correspond to the ground motions from different earthquakes.

and emerging good practice in terms of modelling the epistemic uncertainty in ground motion. Our starting point for this was to convene a meeting of the four members of the project team and four external experts to discuss the key issues that needed to be considered in the development of the maps and to come to a consensus view of what the ground motion model should be like.

Two potential approaches were discussed: the "traditional" multi-GMPE logic tree approach and the backbone approach (see Douglas, 2018 for review). In the UK, the multi-GMPE logic tree approach has been used in the ground motion characterisation model of Tromans et al. (2018), which was developed for the new nuclear site at Hinckley Point in Somerset. This consists of five GMPEs, which represent a range of tectonic environments: stable continental region (Atkinson and Boore, 2011), active shallow crustal regions (Cauzzi et al., 2015; Bindi et al., 2014; and Boore et al., 2014), and a stochastic model for the UK (Rietbrock et al., 2013). The backbone approach of Douglas (2018) takes the GMPE of Kotha et al. (2016) as its reference and this GMPE is scaled up and down to account for epistemic uncertainties in the median prediction.

After the workshop, both approaches were investigated. Following various tests it was agreed that the multi-GMPE model of Tromans et al. (2019) was preferable for two reasons. Firstly, its suitability for application in the UK had already been assessed and secondly, the scaling factors in Douglas (2018) have not been computed for 0.2 s period spectral acceleration. We use the sigma model of Tromans et al. (2019) to characterise the epistemic uncertainties in the τ model (inter-event variability) and the single station φ model (intra-event variability).

Outputs will include publically available maps of seismic hazard for key return periods (95 years, 475 years and 2475 years), an open-access report describing the model, a presentation at a SECED evening meeting to present the results, and a peer-reviewed publication in a relevant journal. The results will also be presented at the SECED2019 conference in Greenwich (9-10 September) - https://www.seced.org.uk/index.php/seced-2019.



Frequency Magnitude plots for the combined historical and instrumental catalogue and for the instrumental and historical catalogues separately.

Research

Objective Quantification of Seismic Source Models

We have developed a new method for characterising seismic source zone models (SZM) parameters used in probabilistic seismic hazard assessment (PSHA) using a combination of Monte Carlo sampling and Bayesian inference that allows us to capture multiple sources of uncertainty.

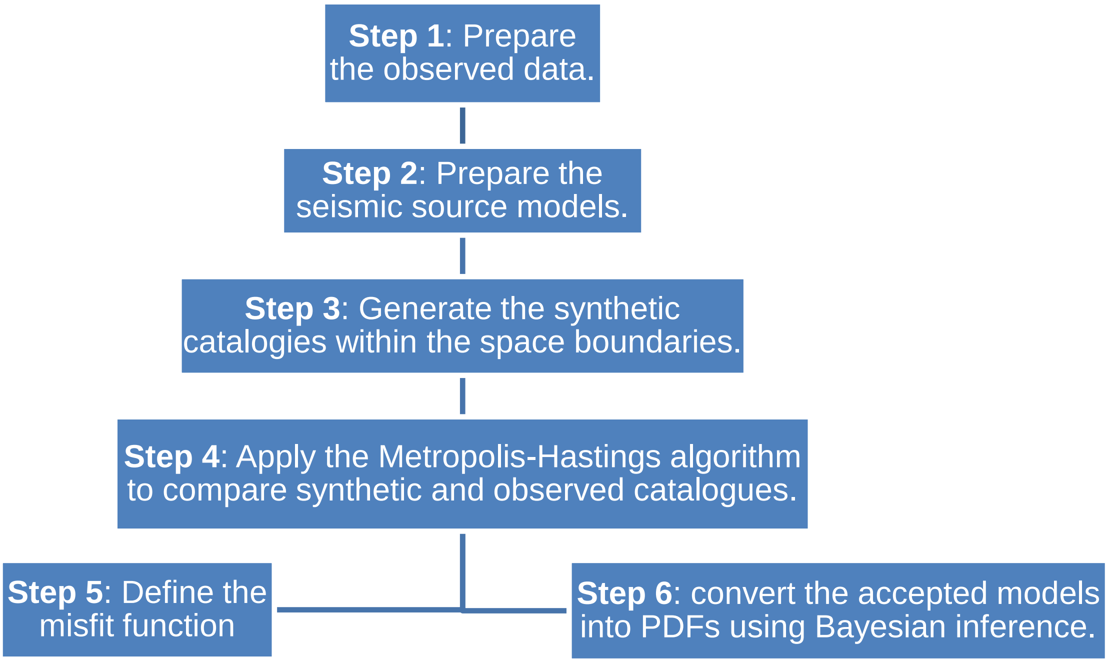
PSHA is generally used for the seismic design of critical facilities in areas of low seismicity, including the UK. Following SSHAC guidelines (Budnitz et al., 1997; USNRC, 2012), current practice of PSHA in the nuclear industry is to express the seismic source characterization (SSC) model and the ground motion characterization model as logic trees to capture the centre, body and range of the technically defensible interpretations. The likelihood of fully capturing the uncertainty in key SSC models is achieved by including alternative models and parameter values in the logic tree where weights are assigned to each branch by expert judgements that reflect the relative confidence in those models and parameters (Coppersmith and Bommer, 2012). The judgement of experts introduces some degree of subjectivity, especially in regions of low to moderate seismicity such as the UK, where the data from geology, geophysics, tectonics and seismology can be interpreted in different ways.

We have developed a fully non-linear methodology for quantitative assessment of a SSC model based on the Bayesian statistical analysis to model jointly the key components of the SSC model and to fully capture their uncertainty. This approach provides an objective way to test different SSC models.

The approach combines Monte Carlo sampling with Bayesian inference. The Monte Carlo approach allows us to sample many potential models compatible with the data and account for the non-linear and complex relationship between the model and the data. We use the Metropolis-Hastings algorithm because it is less computationally expensive than other Monte Carlo methods and is relatively efficient in high-dimensioned model space.

We also use Bayesian inference to update the probability for a given model based on the observed data and translate the set of models generated by the Metropolis-Hastings algorithm into probability density functions (PDFs), which can be used to infer trade-off and dependencies between the model parameters.

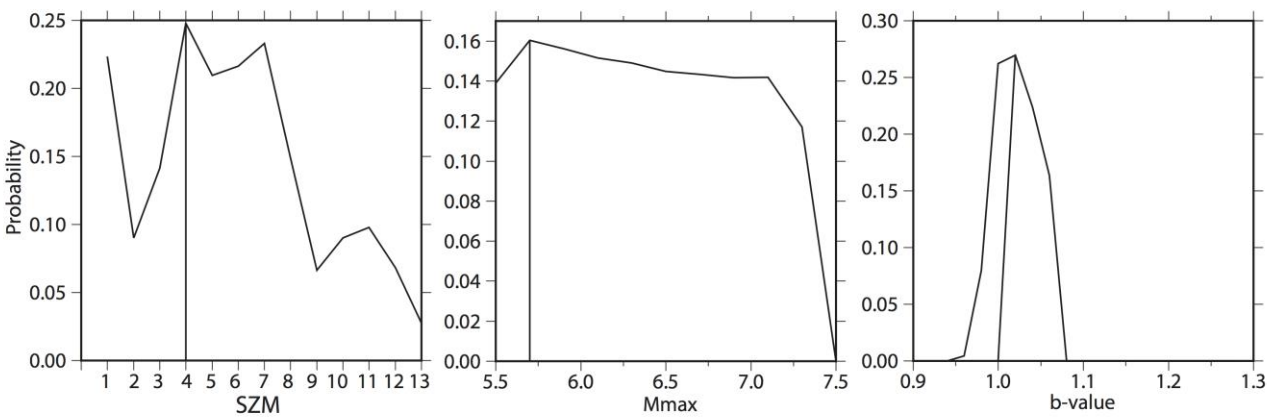
The approach was applied to the Wylfa Newydd nuclear site (Isle of Anglesey, UK), one of several proposed sites for new nuclear power plants in the UK. Thirteen SZMs were selected, most of which were developed for regional or site-specific PSHA. Each SZM is described by a set of parameters, including the geometry of the source zones, lower and upper bounds of the magnitude range and recurrence



Workflow for the Bayesian Metropolis-Hastings approach.

parameters from the Gutenberg-Richter law.

Synthetic catalogues are generated for randomly chosen SZMs. The set of synthetic catalogues that best-fit the data (i.e. the observed earthquake catalogue) are converted into posterior PDFs, one for each model parameter. The posterior PDFs can then be used to rank the set of model parameters of the SZM and to define the source model weighting in a logic tree. This provides high confidence in the logic tree for the source model because the centre, body, and range of the technically defensible interpretations for the SSC models are included in the PDFs.



Posterior PDFs for a set of model parameters. The solid lines describe the most likely value.

Research

A New Framework for Discriminating Induced Seismicity

Researchers at the University of Bristol, British Geological Survey and Imperial College London have developed a new framework for assessing whether earthquakes occurring near to subsurface industrial activity have a natural cause or are induced. The new approach was applied to the Newdigate sequence with the conclusion that the earthquakes were natural rather than induced. This work has now been published in Seismological Research Letters.

Robust methods are needed to assess whether detected earthquakes near industrial sites are natural or induced by the industrial activity. However, the most commonly used approach, the question based scheme suggested by Davis and Frohlich (1993) has a number of shortcomings that became apparent in the assessment of whether or not the Newdigate earthquake sequence in 2018/2019 had been induced by nearby hydrocarbon exploration and production. For example: not specifically addressing the question of whether available evidence supports the case against induced seismicity; giving all questions equal weighting regardless of the relative influence of the different factors in determining whether or not seismicity is induced; producing final outcomes that may be difficult to interpret.

In a recently published paper, Verdon et al (2019) propose a new question-based framework that addresses these shortcomings by assigning numerical scores to each question, with positive values for answers that support induced seismicity and negative values for responses favouring natural seismicity.

The scores available for each question reflect the relative importance of the different questions, and for each question the absolute value of the score is modulated according to the degree of uncertainty.

When applying the framework, the first step is to assess how much information is available for each question. This then defines the first outcome, which we call the Evidence Strength Ratio (ESR), which is the ratio of the maximum score that can be assigned with the available data to the maximum score that would be available in an ideal case with all desirable data fully available.

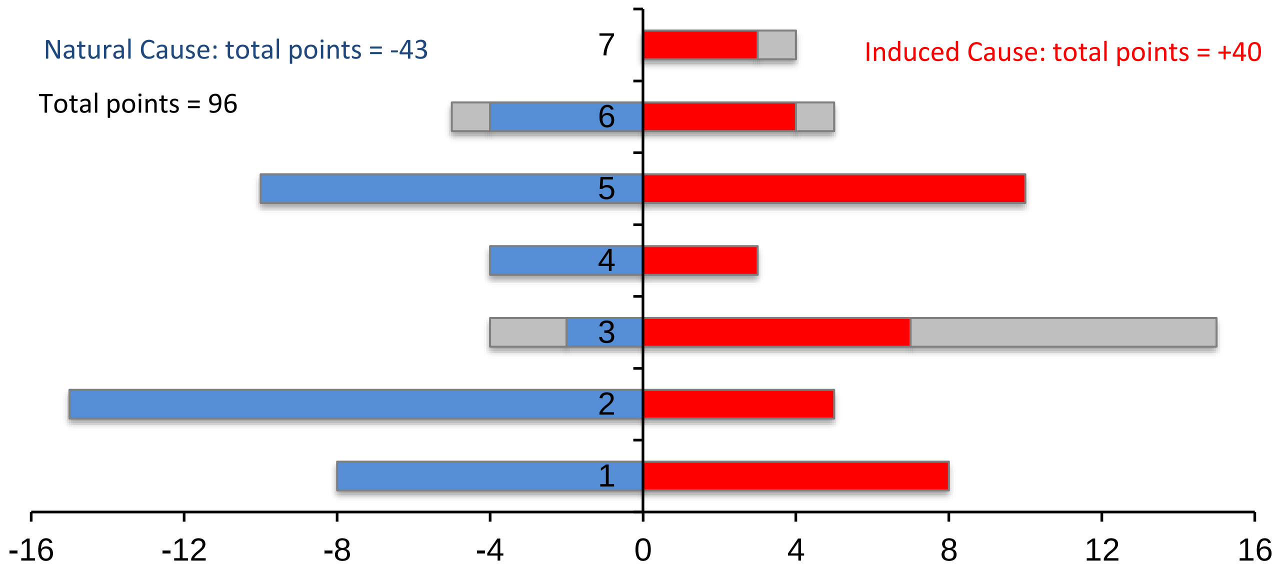
$$ESR = \frac{(|-ve\ points| + |+ve\ points|)}{Absolute\ number\ of\ points}$$

A low ESR suggests that relatively little information is available for the assessment, while a high ESR suggests that much more data is available.

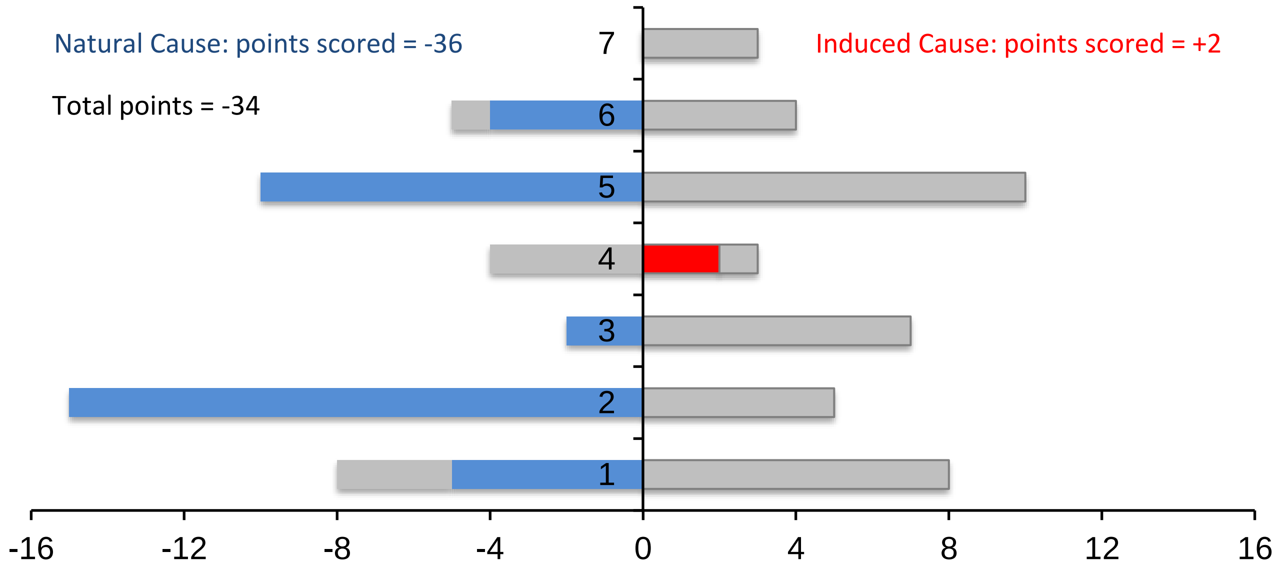
The second outcome is the Induced Assessment Ratio (IAR), which quantifies whether the overall assessment indicates a natural or an induced cause. The total number of points scored across each criterion, combining both positive and negative values, is expressed as a ratio of the maximum points that could have been scored if all answers were positive (if the summed score is positive) or negative (if the summed score is negative).

$$IAR = \frac{Summed\ Score}{Maximum\ points\ available}$$

A positive IAR value indicates an induced cause, while a negative IAR indicates a natural cause. However, low values should be interpreted as an ambiguous assessment, based on insufficient data (low ESR).



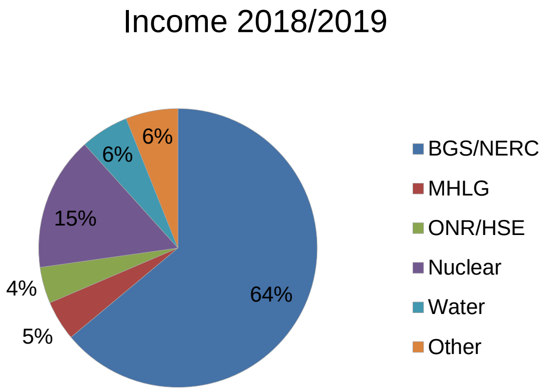
Schematic illustration of the evidence strength ratio (ESR) for an example with a relatively strong ESR. Gray shaded arrows show the maximum points available for each question given the best possible quality evidence. A total of 83 from 96 points could be scored, so the ESR is 87%. This figure is based on our scoring for the Newdigate sequence relative to the Horse Hill well as assessed after a full study of the sequence.

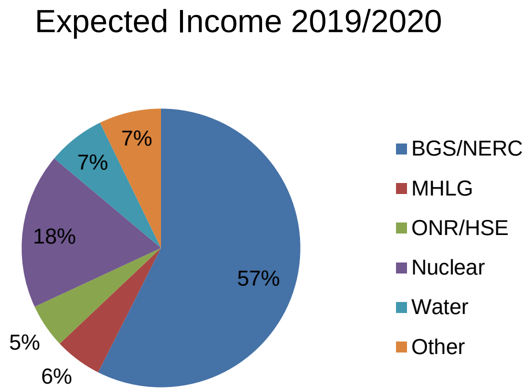


Schematic illustration of the induced assessment ratio (IAR). A total of 36 negative points and two positive points are scored, giving an IAR of −34/43 = −79%. Such a strongly negative value indicates that the evidence points firmly towards these events not being induced by the industrial activity being examined. This figure is based on our scoring for the Newdigate sequence relative to the Horse Hill well as assessed after a full study of the sequence.

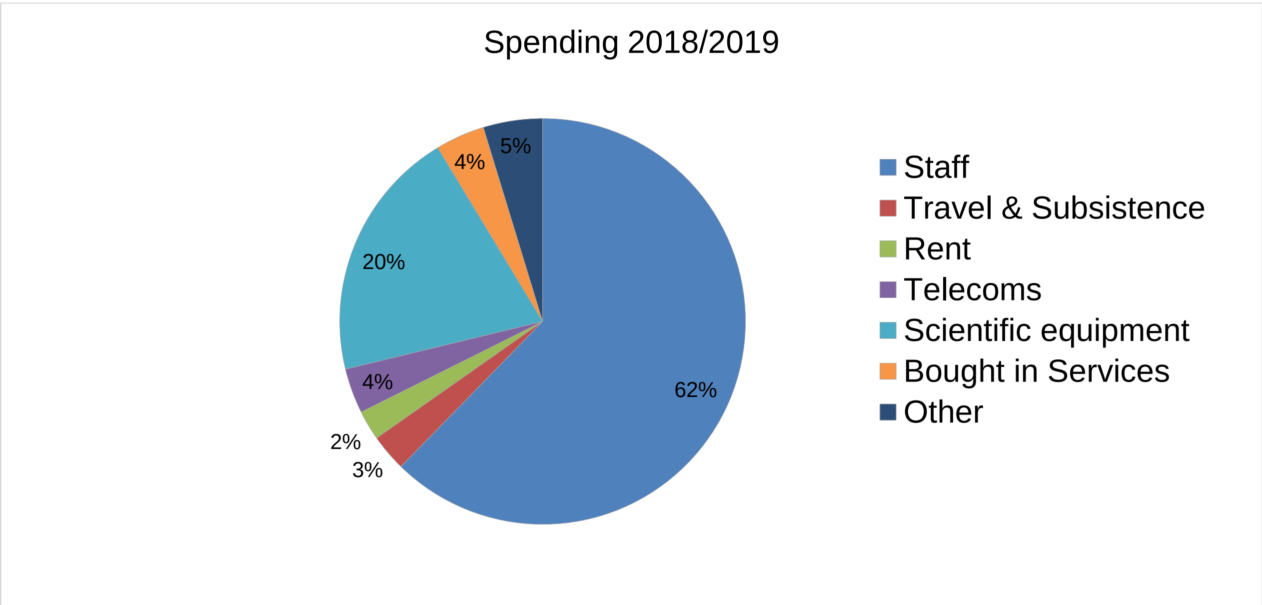
Funding and Expenditure

In 2018-2019 the project received a total of £852K, including a contribution of £580K from NERC. This included £138K of capital funding to replace the equipment that was deployed in Surrey to study the earthquake activity around Newdigate as well as seven new data loggers. The funding was provided through a successful proposal submitted to the BGS Capital Committee. This was matched by a total contribution of £272K from the Customer Group drawn from industry, regulatory bodies and central and local government.





The projected income for 2019-2020 from the Customer Group is £270K. The NERC contribution for 2019-2020 currently stands at £438K, but we hope to increase this through applications for additional funding through the year.



Total spending in 2018/2019.

A Strategy for the BGS NEIS

It was recognised that there was a need for a strategy document (Baptie and Walker, 2019) to highlight achievements, and focus on the direction in which the project would take over the next 5 years. To this end, the draft strategy was circulated to Customers in March 2019 inviting comments and feedback. It presents:

- A summary of the history of the NEIS showing how it has developed from its inception in the mid-1970s.
- A description of the major functional units within the NEIS project, how these operate and what outputs and deliverables are produced to inform stakeholders.
- A Strengths Weaknesses Opportunities and Threats (SWOT) analysis of current operations to enable recommendations to be made to support development and improvement of the NEIS going forwards.
- A Forward Plan that sets out in detail how the SWOT recommendations can be implemented through a defined set of activities for the next three years.

We would like to thank Pete Ford (formerly ONR) and Dave Anderson (Magnox) for their valuable advice and contributions to earlier versions of the document. The intention is to update the strategy annually to keep abreast of developments and achievements.

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, Horizon Nuclear Power, Jersey Water, Magnox Ltd., the Office for Nuclear Regulation, Sellafield Ltd, Drax Group plc, Scottish Water, SSE and BRBGenCo (formally welcomed in March 2019 following engagement through a site-specific monitoring project). 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.
Susanne Sargeant	Seismic hazard and NERC Knowledge Exchange Fellow.
Margarita Segou	Earthquake forecasting and improving understanding of earthquake triggering mechanisms.

Appendix 2 Publications

Baptie, B. and R. Luckett (2018). The Newdigate earthquake sequence, 2018. British Geological Survey Open Report, OR/18/059.

Baptie, B. (2018). Is Earthquake Activity in the Northern British Isles Driven by Glacio-Isostatic Recovery? In D'Amico, S., Galea, P., Bozionelos, G., Colica, E., Farrugia, D. and Agius, M.R. (Eds.), Proceedings of the 36th General Assembly of the European Seismological Commission, ISBN: 978-88-98161-12-6.

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Marra,G., C. Clivati, R. Luckett, A. Tampellini, J. Kronjäger, L. Wright, A. Mura, F. Levi, S. Robinson, A. Xuereb, B. Baptie and D. Calonico (2018). Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables. *Science* **361**, 486–490, DOI: 10.1126/science.aat4458

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Appendix 3 Publication Summaries

The Newdigate earthquake sequence, 2018

B Baptie and R. Luckett, 2018

A sequence of small earthquakes was recorded near Newdigate, Surrey, between 1 April and 31 August 2018. The largest had a magnitude 3.0 ML and four others had magnitudes of greater than 2.0 ML. Seven of the earthquakes were felt by people living nearby and there was public concern that the earthquake sequence may have been triggered by nearby hydrocarbon exploration and production. Five temporary sensors were installed by BGS in mid-July close to the epicentral area. Our analysis shows that earthquake epicentres are tightly clustered in a 3 km by 3 km source zone that lies between the villages of Newdigate and Charlwood, and at a distance of approximately 8 km from the Brockham oil field. Depths calculated using only recordings at distances of up to 10 km suggest that the events are most likely to have occurred at depths of approximately 2 km. We use the criteria suggested by Davis and Frohlich (1993) to assess the available evidence that the earthquake sequence may have been induced. This suggests that the events are unlikely to have been induced.

Is Earthquake Activity in the Northern British Isles Driven by Glacio-Isostatic Recovery?

B. Baptie, 2018.

A number of authors have suggested that main cause for earthquake activity in northern Britain is deformation associated with glacio-isostatic recovery. This appears to be mainly based on the correlation between the spatial extent of the seismicity in northwest Scotland and the region of maximum ice thickness during the last glacial maximum, rather than the properties of the earthquakes or the measured strain field. Detailed analysis of spatial distribution of observed seismicity suggests that most clusters of earthquake activity are associated with steeply dipping faults that strike approximately NE-SW or NW-SE. Similarly, focal mechanisms determined for instrumentally recorded earthquakes consistently show strike-slip faulting with N-S compression and E-W tension, which results in either left-lateral strike-slip faulting along near vertical NE-SW fault planes, or right-lateral strike-slip faulting along near vertical NW-SE fault planes. These trends match the recent geological history of the large-scale fault structures in British Isles where Alpine-related compression has driven faulting. In addition, the strain rate field calculated from continuous Global Positioning System measurements also exhibits predominantly left-lateral strike-slip loading along a NE-SW trend. These results suggest that earthquake activity across the region is driven by reactivation of favourably oriented, steeply dipping fault systems by deformation associated with first-order plate motions rather than deformation associated with glacio-isostatic recovery.

A Strategy for the BGS National Earthquake Information Service.

B. Baptie and A. Walker, 2019

The British Geological Survey (BGS) operates a UK-wide seismic monitoring and information service to record, locate and analyse UK seismicity, to provide advice to UK Government, the public and to a number of commercial and utility agencies with an interest in UK seismicity, and to archive this information for the benefit of research. This is the BGS National Earthquake and Information Service (NEIS) project. The NEIS is managed on a day-to-day basis by a dedicated team of expert professional staff. Funding for the NEIS is provided primarily by the Natural Environment Research Council (NERC) and matched by contributions from a number of UK Government, utility and similar organisations who have a specific interest in UK seismicity, known collectively as the Customer Group. Recently, at an annual meeting of the Customer Group, the project manager was requested to critically examine the current operations of the NEIS and draw up a strategic plan to justify its current modus operandi, or recommend changes thereto, to ensure that the NEIS continues to provide the best possible service to all its stakeholders.

The Bulletin of British Earthquakes 2018.

D. Galloway, 2019

The British Geological Survey's (BGS) Seismic Monitoring and 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 2018.

Maps showing seismic activity in 2018 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 (12°W to 6°E and 48°N to 64°N).

Extending local magnitude ML to short distances.

R. Luckett, L. Ottemöller, A. Butcher and B. Baptie, 2019

Local magnitudes calculated at stations less than 10 km from earthquakes in the British Isles are up to one unit of magnitude higher than local magnitudes calculated at more distant stations. This causes a considerable overestimate of the event magnitude, particularly for small events, which are only recorded at short distances. Data from Central Italy and Norway show that the same problem also occurs in other regions, suggesting that this is a more general issue for local magnitude scales. We investigate the addition of a new exponential term to the general form of the local magnitude scale. This corrects for the higher-than-expected amplitudes at short hypocentral distances. We find that the addition of this new term improves magnitude estimates in the three studied regions and magnitudes at short distances are no longer overestimated. This allows the use of a single scale that can be used at all distances, with a smooth transition between short and long distances. For the UK, the amended scale is

$M_L = \log(amp) + 1.11\log(r) + 0.00189r - 1.16e^{-0.2} - 2.09$ and this is the scale now used by the British Geological Survey.

Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

G. Marra, C. Clivati, R. Luckett, A. Tampellini, J. Kronjäger, L. Wright, I. Mura, F. Levi, A. Robinson, A., Xuereb, B. Baptie and D. Calonico, 2018

Detecting ocean-floor seismic activity is crucial for our understanding of the interior structure and dynamic behavior of Earth. However, 70% of the planet's surface is covered by water, and seismometer coverage is limited to a handful of permanent ocean bottom stations. We show that existing telecommunication optical fiber cables can detect seismic events when combined with state-of-the-art frequency metrology techniques by using the fiber itself as the sensing element. We detected earthquakes over terrestrial and submarine links with lengths ranging from 75 to 535 kilometers and a geographical distance from the earthquake's epicenter ranging from 25 to 18,500 kilometers. Implementing a global seismic network for real-time detection of underwater earthquakes requires applying the proposed technique to the existing extensive submarine optical fiber network.

Integrating outcomes from probabilistic and deterministic seismic hazard analysis in the Tien Shan

I. Mosca, B. Baptie, S. Sargeant and R.T. Walker, 2019

In this study, we have evaluated the probabilistic and deterministic seismic hazard for the city of Almaty, the largest city in Kazakhstan, which has a population of nearly two million people. Almaty is located in the Tien Shan belt, a low-strain-rate environment within the interior of the Eurasian plate that is characterized by large infrequent earthquakes. A robust assessment of seismic hazard for Almaty is challenging because current knowledge about the occurrence of large earthquakes is limited, due to the short duration of the earthquake catalog and only partial information about the geometry, rupture behavior, slip rate, and the maximum expected earthquake magnitude of the faults in the area. The impact that this incomplete knowledge has on assessing seismic hazard in this area can be overcome using both probabilistic and deterministic approaches and integrating the results. First, we simulate ground-shaking scenarios for three destructive historical earthquakes that occurred in the northern Tien Shan in 1887, 1889, and 1911, using ground-motion prediction equations (GMPEs) and realistic fault-rupture models based on recent geomorphological studies. We show that the large variability in the GMPEs results in large uncertainty in the ground-motion simulations. Then, we estimate the seismic hazard probabilistically using a Monte Carlo-based probabilistic seismic hazard analysis and the earthquake catalog compiled from the databases of the International Seismological Centre and the British Geological Survey. The results show that earthquakes of M w Mw 7.0–7.5 at Joyner–Boore distances of less than 10 km from the city pose a significant hazard to Almaty due to their proximity. These potential future earthquakes are similar to the 1887 Verny earthquake in terms of their magnitude and distance from Almaty. Unfortunately, this is the least well understood of the destructive historical earthquakes that have occurred in the northern Tien Shan.

A New Technique to Estimate Fault Potential and Aftershock Forecasts

M. Segou, T. Parsons and J. Mori, 2018.

During the last few decades the implementation of Coulomb stress changes is the main method for explaining the stress transfer hypothesis. The initial enthusiasm of the early 90s for understanding the physics behind aftershock occurrence has faded in recent years as more high-quality datasets make possible a broader hypothesis testing that now challenges longstanding ideas about the efficiency of static stress changes. Recent literature supports that the spatial distribution of aftershocks can be explained by the co-seismic fault loading, described by static stress changes. However, the observed stress shadows and the estimated optimal oriented for failure fault planes are often inconsistent with the inferred stress changes. A critical view of Coulomb stress changes framework is required to evaluate how simple assumptions and current triggering concepts affect the success rates of forecast models. A new technique is presented based on the consideration of the total stress field, taken as the sum of the pre-seismic and the co-seismic stress tensor, and all possible fault planes. Under a positive failure condition we determine the probable planes. We then compare the results for probable and optimally oriented failure planes. In order to illustrate our extended solution space (app. 1M stress estimates per geographical grid point), we use 2D histograms (Euclidean Distance of Strike/Dip vs. Rake), frequently used in DNA sequencing. We use premainshock focal mechanisms, geological fault structures and spatially varying maximum horizontal axis orientation to represent the regional stress field. We compare estimated and observed 2D histograms to determine if there is at least one common combination of parameters in which the model can reproduce the observed rupture style of aftershocks. We use the new model to answer the questions: (1) Do earthquakes occur on maximum-stressed planes? (2) How does pre-mainshock stress heterogeneity controls aftershock populations?, (3) How often do aftershock ruptures happen on optimally oriented planes?, (4) How do long-term nucleation probabilities change when we move from an ideal fault zone representation to complex diverse multi-branching fault systems? We present results from 3 earthquake sequences in California, Japan and Italy, which are known for complex faulting patterns and diversity of aftershocks and foreshocks; the M=7.2 2010 El Mayor-Cucapah, the 2016 M=7.0 Kumamoto and the 2009 M=6.4 L'Aquila sequences. We find a low success ratio (=number of consistent aftershock ruptures/total number of aftershocks) for optimal planes (0.22-0.35) whereas the new technique which includes heterogeneity in the form of pre-seismic ruptures, reaches a high success ratio (0.70-0.82). Furthermore, we find that aftershocks do not usually occur on the maximum stressed faults since this criterion leads to very low success ratios (0.02-0.18). The latter finding has implications for short and long-term earthquake hazard studies, since it shows that critically loaded faults in different times within their loading cycles may be triggered even with a small stress perturbation.

An improved framework for discriminating seismicity induced by industrial activities from natural earthquakes.

J.P. Verdon, B.J. Baptie, and J.J. Bommer, 2019.

Heightened concerns regarding induced seismicity necessitate robust methods to assess whether detected earthquakes near industrial sites are natural or induced by the industrial activity.These assessments are required rapidly, which often precludes detailed modeling of fluid pressures and the geomechanical response of the reservoir and nearby faults. Simple question based assessment schemes in current use are a useful tool but suffer from several shortcomings: they do not specifically address questions regarding whether available evidence supports the case for natural seismicity; they give all questions equal weighting regardless of the relative influence of different factors; they are not formulated to account for ambiguous or uncertain evidence; and the final outcomes can be difficult to interpret. We propose a new framework that addresses these shortcomings by assigning numerical scores to each question, with positive values for answers that support induced seismicity and negative values for responses favoring natural seismicity. The score values available for each question reflect the relative importance of the different questions, and for each question the absolute value of the score is modulated according to the degree of uncertainty. The final outcome is a score, the induced assessment ratio, either positive or negative (or zero), that reflects whether events were induced or natural. A second score, the evidence strength ratio, is assigned that characterizes the strength of the available evidence, expressed as the ratio of the maximum score possible with the available evidence relative to the maximum score that could be obtained if all desired data were available at a site. We demonstrate this approach by application to two case studies in the United Kingdom, one widely regarded as a case of induced seismicity, and the other more likely to be a series of tectonic earthquakes.

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