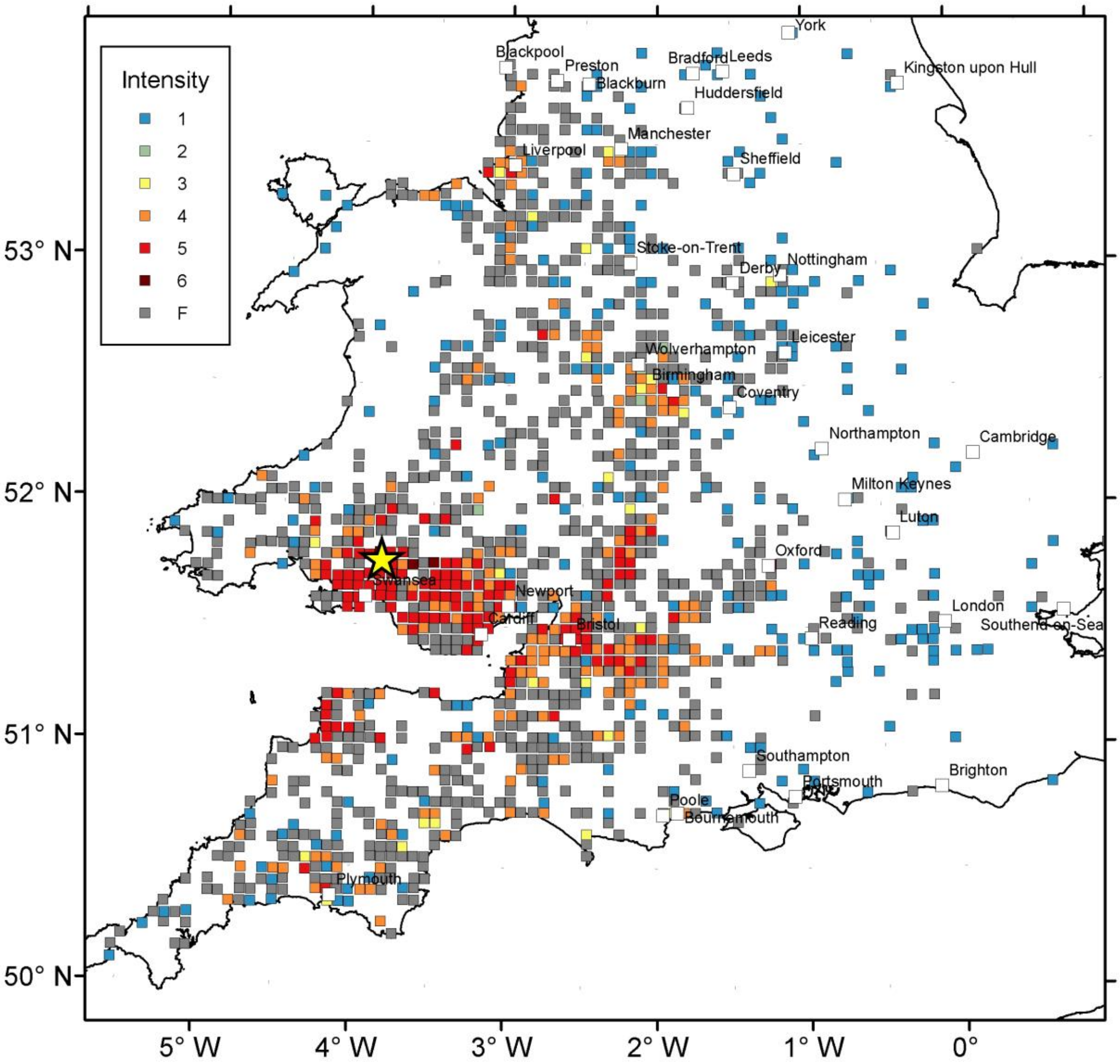
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Earthquake Seismology 2017/2018

BGS Seismic Monitoring and Information Service

Twenty-ninth Annual Report



BRITISH GEOLOGICAL SURVEY

OPEN REPORT OR/18/029

Earthquake Seismology 2017/2018

B. Baptie (editor)

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Front cover

Macroseismic intensities (EMS) calculated for the magnitude 4.6 ML South Wales earthquake on 17 February 2018.

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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 Seismic Monitoring and Information Service 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 29th year of the project, we have continued to operate the national seismic monitoring network efficiently and effectively. Real-time data from all stations were transferred directly to Edinburgh for near real-time detection and location of seismic events as well as archival 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).

Three papers have been published in peer-reviewed journals and three BGS reports were prepared. We have continued to collaborate widely with academic partners across the UK and overseas on a number of research initiatives.

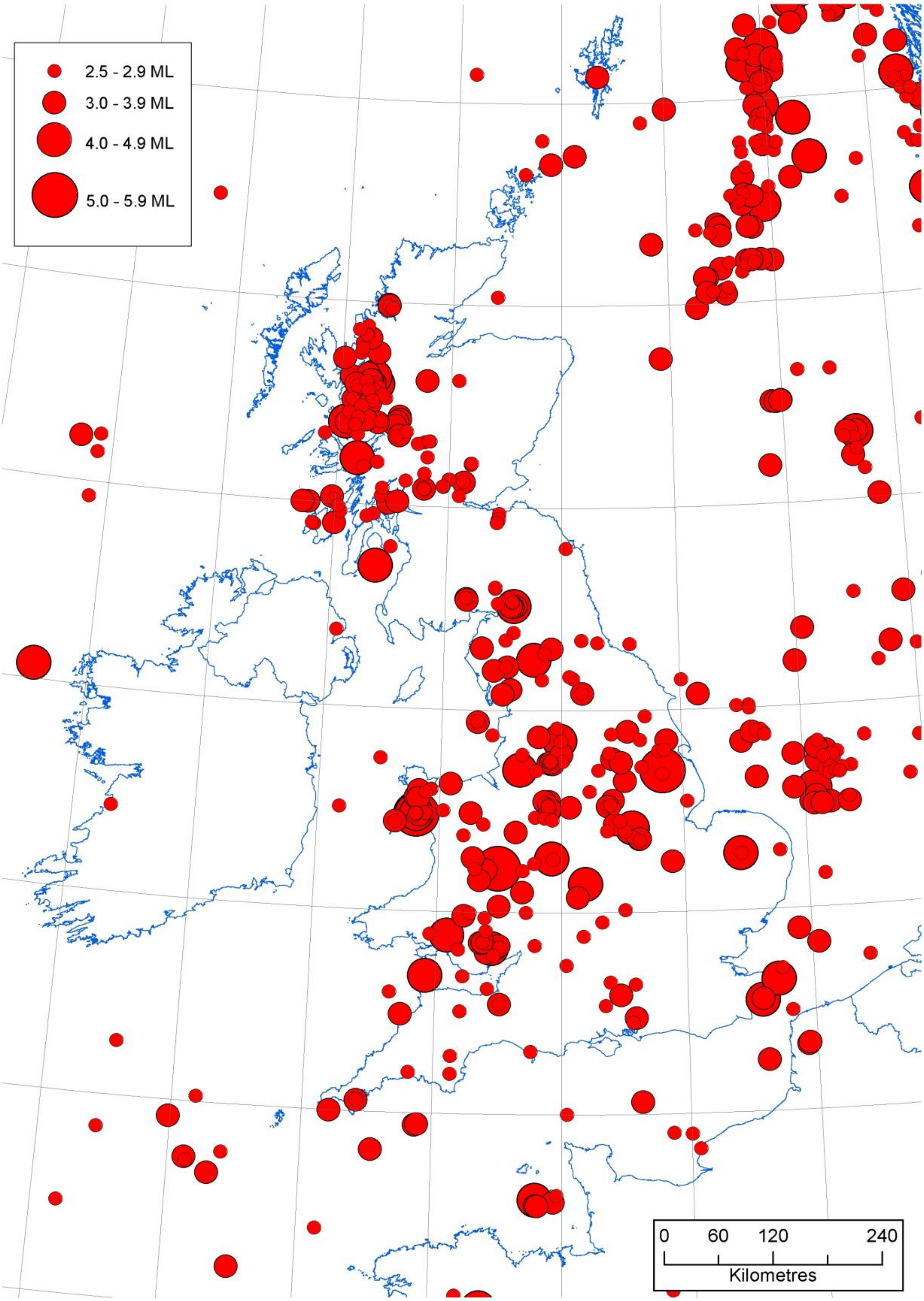
Introduction

The BGS Seismic Monitoring and Information Service has developed 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 2018.

Monitoring Network

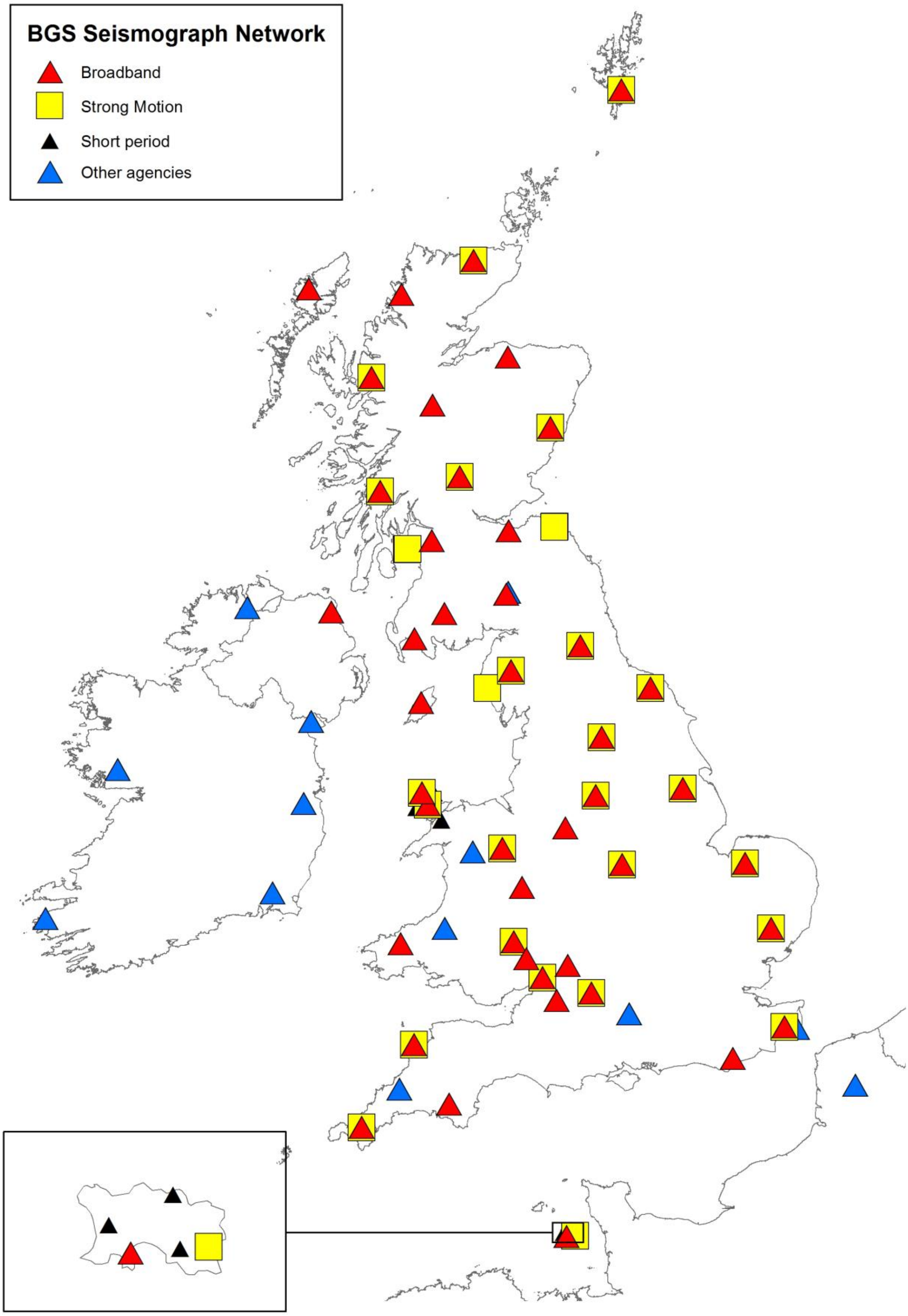
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late 1990s, the number of stations reached its peak of 146, with an average spacing of 70 km. The current network 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 44 broadband seismometers at stations across the UK along with 32 strong motion accelerometers with high dynamic range for recording very large signals.



BGS seismograph stations, March 2018

Achievements

Network Performance

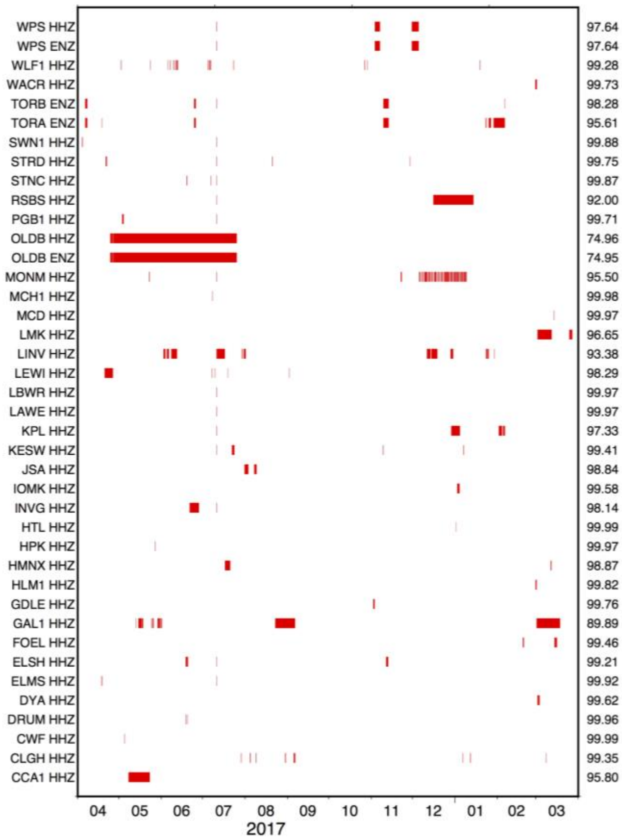
The network contains 44 broadband sensors with 24-bit acquisition which provide real-time data from across the UK. Significant faults were rapidly identified and remedied. Data completeness is high. A new strong motion alarm system was installed at Hunterston Nuclear Power station.

The network currently consists of 44 broadband sensors, 32 strong motion sensors and 6 short period sensors. In the last year the station MCD in Moray was upgraded with a broadband sensor and 24-bit data acquisition. A new strong motion alarm system was installed at Hunterston Nuclear Power station. Short period stations in old Moray and Galloway sub-networks were removed from service. Continuous data from all stations are transmitted in real-time to Edinburgh, where they are used for analysis and archived.

Two new stations operated by the AWE Blacknest and the Dublin Institute of Advanced Studies in Dover, Kent, and County Louth, Ireland, respectively, have been incorporated into our near real-time processing to improve our detection capability.

We are now using automated software processes to identify equipment faults rapidly. These include both gross errors such as data gaps or failures in timing, as well as indicators such as low voltages or high levels of tilt. These routines run on a daily, weekly and monthly basis to allow the aggregate effects of small but repetitive faults to be identified.

In 2017/18 around 150 separate significant faults were identified using these methods. The bulk of these faults were dealt with either remotely, or with the help of a network of local contacts. However, 61 stations required a visit by field section staff. 33 of these were to UKArray sites (see page 7). To improve efficiency we combine multiple site visits into a single trip, and, if appropriate, use lone working.



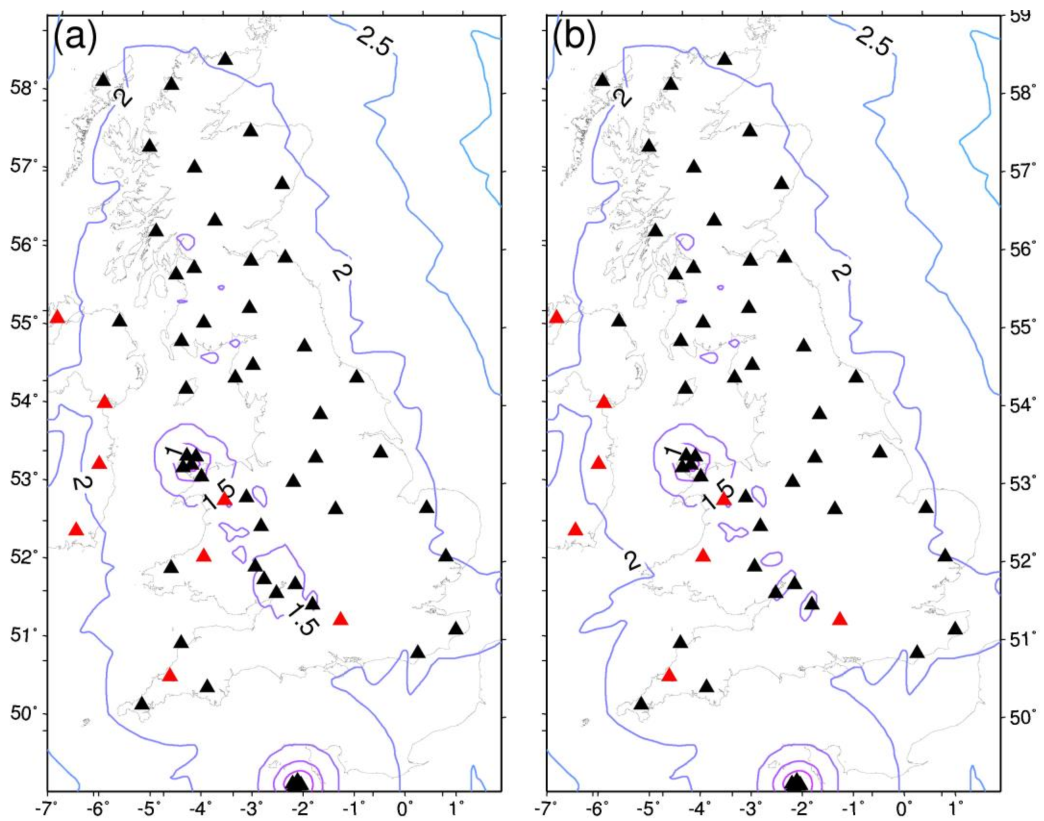
Data completeness for all broadband stations that operated throughout 2017/2018. Data are more than 95% complete 79% of the time, 90% complete 89% of the time and 85% complete 93% of the time.

During the year, 234 person days were spent on fieldwork, with 105 days spent on maintenance of permanent monitoring stations and 91 days on fieldwork associated with the UKArray experiment or the Department for Business, Energy and Industrial Strategy (BEIS) Environmental Baseline Monitoring project in the Vale of Pickering and the Fylde Peninsula. An additional 38 days were spent on site specific monitoring.

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 2017-2018, data are more than 95% complete 79% of the time, 90% complete 89% of the time and 85% complete 93% of the time, which is a slight improvement on the previous year when data was 85% complete for more than 90% of stations and more than 90% complete for over 86% of stations.

The worst performing broadband stations were OLDB, Oldbury (75%) and GAL1, Galloway (90%). In the case of Oldbury much of the loss of data resulted because we were unable to access the site for a period of time. This was resolved in July 2017. Loss of data at GAL1 resulted from equipment failure that was concurrent with communications failures.

In addition, fewer than two stations were down at the same time 62% 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 December 2017, two stations, MONM and RSBS were down at the same time. This does not have a significant effect on overall detection capability.



Detection capability of the network with (a) all stations operational (b) with MONM and RSBS 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

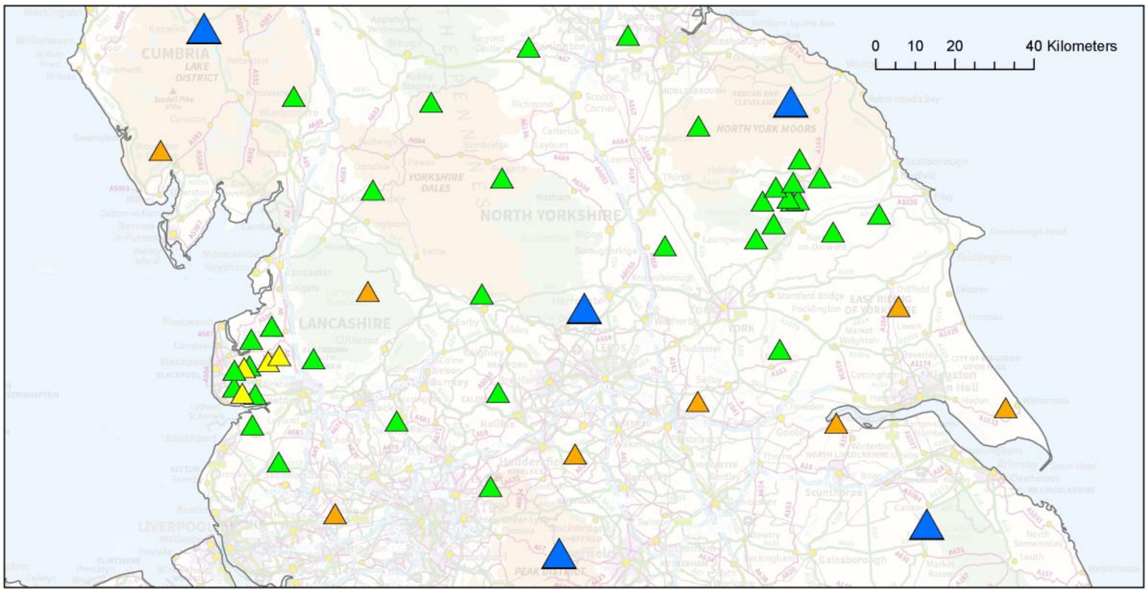
Network Development

We are deploying sensors across the north of England as part of two projects: UKArray and Environmental Baseline Monitoring. Our aim is to provide improved earthquake catalogues, new, detailed models of the Earth's crust under the UK, high resolution images of active fault zones and near real-time information about both natural and man-made seismicity.

In 2015, BGS received over £500,000 from the Natural Environment Research Council (NERC) to purchase forty seismic sensors that could be deployed as an array at different locations across the UK, for a project called UKArray. The project is supported by the universities of Bristol, Edinburgh, Leicester and Liverpool. Our aim is to provide new, detailed models of the Earth's crust under the UK, high resolution images of active fault zones, and near real-time information about both natural and man-made seismic activity including the low magnitude earthquakes commonly associated with industrial activity. The data will also be used to answer fundamental scientific questions about the shallow and deep Earth and to address important issues relating to the future use of the Earth's sub-surface both as a source for sustainable energy and as a means of energy and waste storage.

In addition, we have installed a dense network of sensors in the Vale of Pickering, North Yorkshire (Ward *et al.*, 2017) for an environmental baseline monitoring project that started in 2015 and is funded by the Department for Business, Energy and Industrial Strategy (BEIS). The aim of this project is to collect data that will allow reliable characterisation of baseline levels of the natural seismic activity in the region. This will help discriminate between any natural seismicity and induced seismicity related to future shale gas exploration and production. It will also help to better understand the hazard and mitigate the risk of seismic activity induced by such industrial activities.

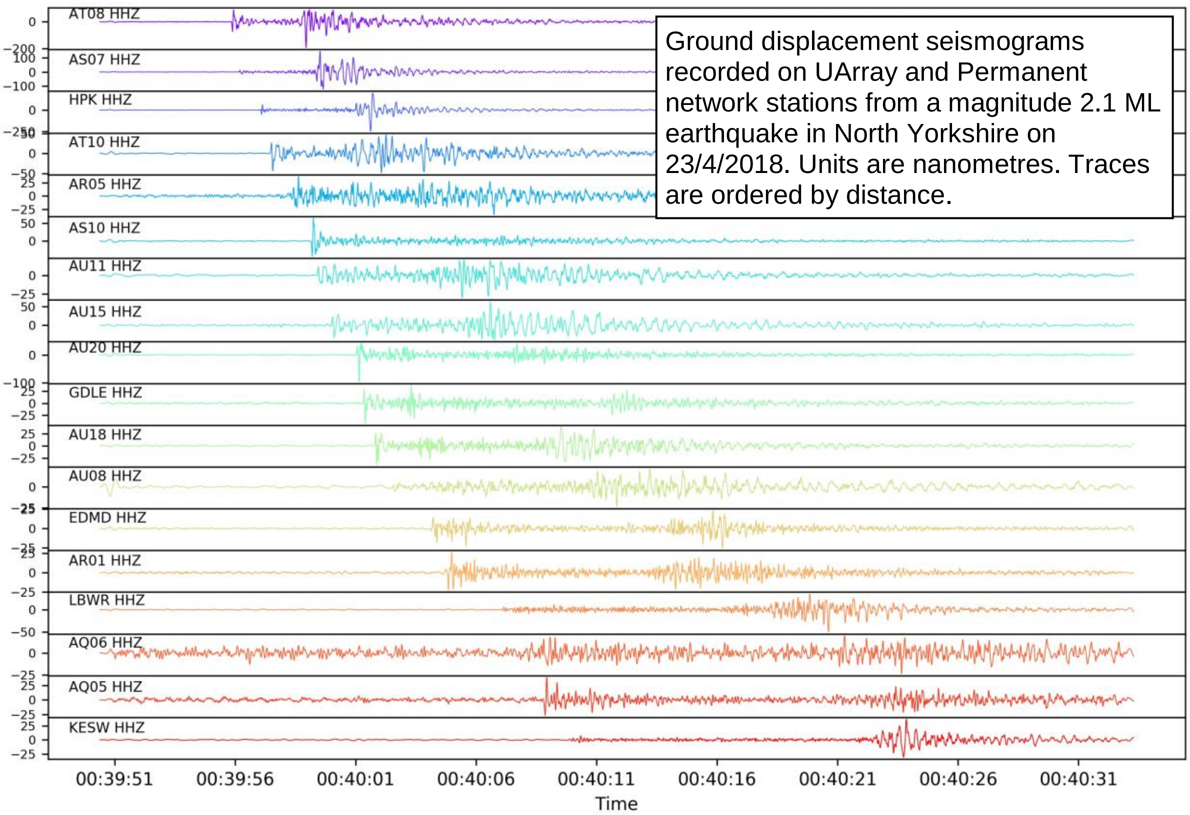
Maintenance at a UKArray site near Kirby Misperton in the Vale of Pickering.



The development of the seismic network in the North of England as a result of the UKArray experiment and the Environmental Baseline Monitoring project in the Vale of Pickering. Blue triangles show permanent stations. Green triangles show temporary stations installed as part of UKArray and the Environmental Baseline Monitoring project. Orange triangles show approximate locations for planned stations. Yellow triangles show temporary stations installed by the University of Liverpool that we have access to data from.

In 2017/2018, we installed eight new UKArray temporary stations, giving a total of 34 stations across the North of England. We plan to install two more stations in 2018/2019.

Continuous data from all installed 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.



Ground displacement seismograms recorded on UArray and Permanent network stations from a magnitude 2.1 ML earthquake in North Yorkshire on 23/4/2018. Units are nanometres. Traces are ordered by distance.

Information Dissemination

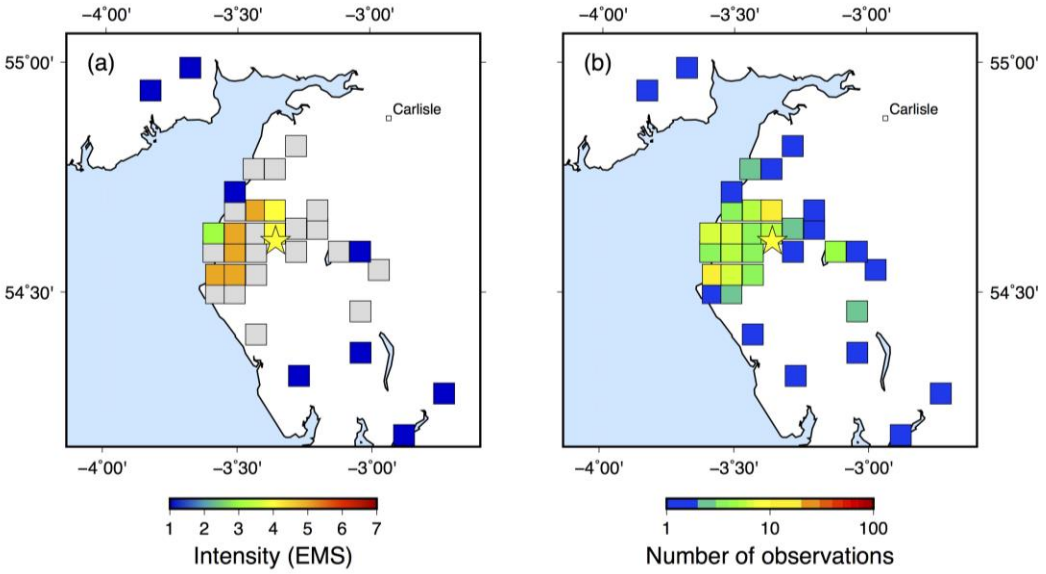
It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received notification by e-mail whenever an event was felt or heard by more than two individuals.

Notifications were issued for 24 UK events within the reporting period. Notifications 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. Seventeen of the alerts were for earthquakes on mainland Britain and a further five were for earthquakes offshore in the waters around the British Isles. The two remaining alerts were for sonic events. No enquiries were received from Nuclear Power Stations in the period April 2017 to March 2018.

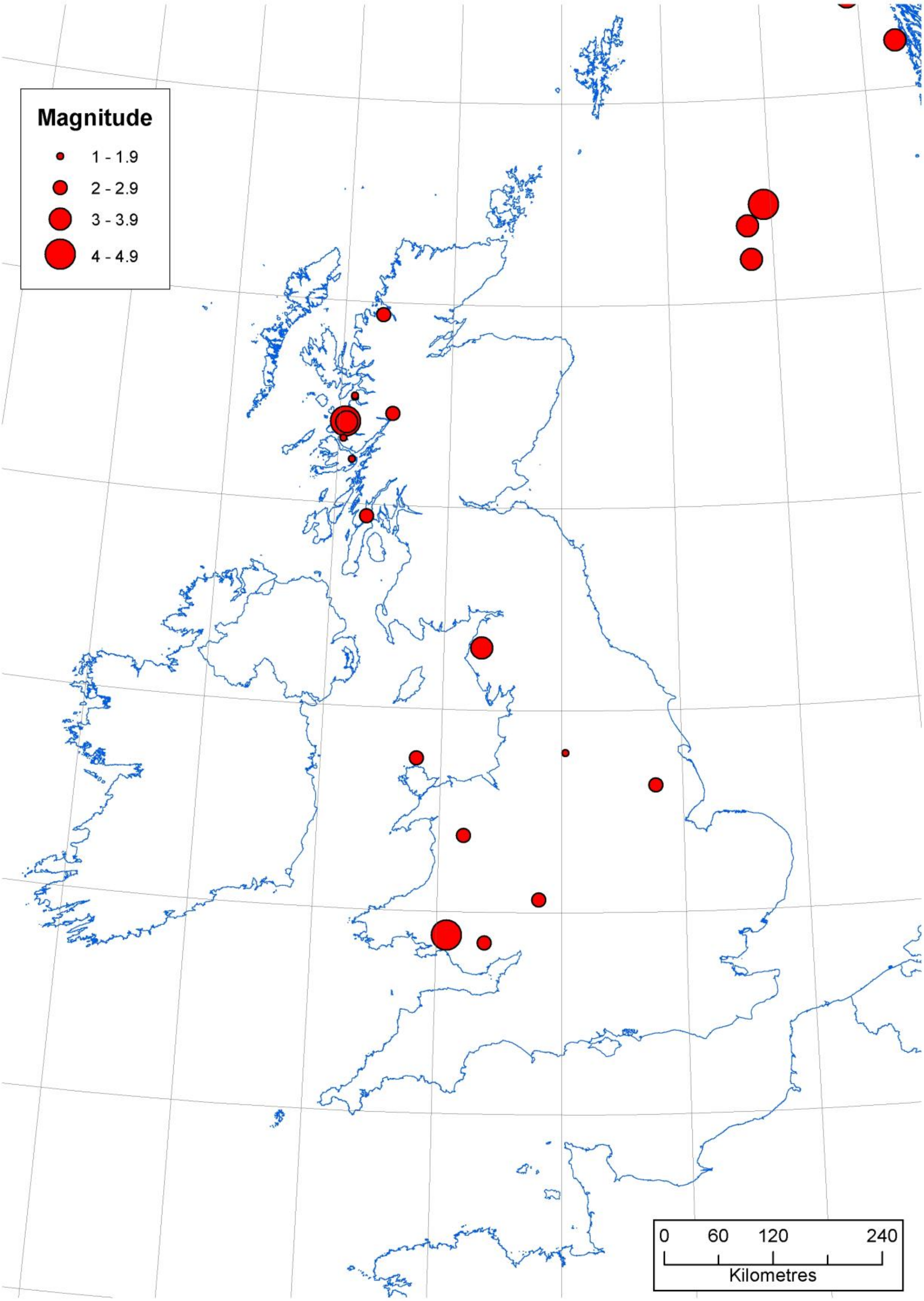
We continue to update the Seismology web pages. These web pages are directly linked to our earthquake database providing near real-time lists of significant earthquake activity, together with automatically generated pages for each event.

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 7,811 replies following the South Wales earthquake on 17 February 2018 (4.6 ML), 353 replies following the magnitude 4.0 ML Moidart earthquake on 4 August 2017 and 110 replies following a magnitude 3.4 ML earthquake near Cockermouth, Cumbria on 28 February 2018.

Updates were circulated to Customer Group members following the South Wales earthquake on 17 February, as new information became available. BGS Open Reports on the South Wales (Baptie et al, 2018) and the Moidart earthquakes (Baptie et al, 2017) were also issued.



Macroseismic intensities for the Cockermouth earthquake on 28 February 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 2017 – 31 March 2018) 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.

BGS staff, including Davie Galloway and Heiko Buxel from the Seismology Team, took part in the “BGS Auroras and Earthquakes” Open Day at Lerwick Observatory, Shetland Islands on 30 June and 1 July 2017. Lerwick Observatory has been running for 95 years as a geomagnetic observatory but it is also home to seismological instruments measuring earthquakes. While the seismologists were on the Island, an earthquake, with a magnitude of 4.7 ML, occurred at 13:33 UTC on Friday afternoon (30 June) in the Central North Sea region, approximately 215 km SE of Lerwick. It was felt across the Shetland Islands and generated a huge amount of interest at the Open Day.

Heiko also represented the Seismology Team at the first BGS Open Day to be held at the Lyell Centre, Edinburgh (the new home of BGS in Scotland) in September 2017. The event gave members of the public the chance to find out about the research at the Lyell Centre including geomagnetism, seismology and volcanology.

Davie Galloway and David Hawthorn from the Seismology Team took part in the NERC showcase event “UnEarthed – Explore the world at your feet”, hosted at Dynamic Earth, Edinburgh, in November. With over 7,000 people, including 20 invited schools, visiting the many BGS displays, it was a massive public engagement for seismology and BGS.

In January, Davie Galloway gave a presentation on earthquakes and volcanoes to pupils from George Heriots School in Edinburgh as part of their natural disasters school project curriculum. Many of the pupils also attended the BGS Unearthed showcase event at Dynamic Earth.

Davie Galloway attended a two day workshop in February 2018 at the Geological Society London on “Educational and Citizen Seismology”. The workshop was organised by Paul Denton, who leads the BGS School Seismology project, and brought together key practitioners in educational and citizen seismology from across the UK, Europe and worldwide. The event was part of the Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) project, an EU-funded Horizon 2020-supported programme that involves 31 partners from 16 European countries. The SERA project started in May 2017 and will last for three years. BGS is leading WP3 Networking Seismo@school outreach programs. The work package includes the following tasks: workshops in educational seismology; resource collation and publication; coordination and interaction with the wider community; science with Seismo@school; integration of citizen seismology and educational seismology.

Brian Baptie gave an invited talk to the Edinburgh Geological Society in March on the subject “Is earthquake activity increasing?” Destructive earthquakes often lead to speculation that earthquake activity is increasing, but is there really any hard evidence to support this? The lecture drew on earthquake statistics and geophysics to discuss this question with notable examples of how earthquake activity rates can change.

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 2017-2018, at least 820 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 over 2.5 million visitors logged in the year (over 15 million hits). Over twice the average monthly number of visitors were recorded in February 2018 following the South Wales earthquake.

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.

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.

Margarita Segou is PI of the project 'The central Apennines earthquake cascade under a new microscope', that successfully received funding from NSFGEO-NERC (NE/R000794/1) in 2017 with Brian Baptie as the Co-I. The project aims to improve understanding of the evolution of long lasting earthquake sequences, such as the Central Apennines earthquake sequence (2016/2017), and to develop tools that can support informed decision-making in the future.

The project is an ambitious international collaboration with partners from UK (BGS, University of Edinburgh, Bristol), USA (University of Stanford, US Geological Survey, Lamont-Doherty Observatory Columbia University) and Italy (INGV). The kick-off meeting for the NERC-NSF project was held at the Istituto Nazionale Geofisica E Vulcanologia (INGV), Rome at the end of January.

In February 2018, Margarita Segou visited the Disaster Prevention Research Institute in Kyoto (Japan) to work with Professor Jim Mori on an investigation of earthquake triggering and the 2016 Kumamoto sequence. The visit was funded by a RCUK-DPRI Kyoto Research Grant.

Margarita and other BGS staff are also participating in a large consortium focused on the multi-hazard aspects of risk modelling. The aim is to implement innovative science together with state of the art instrument deployment in an effort to provide excellent science serving risk reduction practices worldwide.

The NERC funded Earthquakes without Frontiers (EwF) project has been extended for another year and Susanne Sargeant and Ilaria Mosca are continuing to work within a partnership that includes researchers from a number of UK universities (Cambridge, Oxford and Durham among others) and the Overseas Development Institute. EwF is a transdisciplinary research project that aims to increase resilience to earthquakes and landslides in the Alpine-Himalayan Belt, focussing on Kazakhstan, Nepal, Bihar in northern India, and NE China.

Susanne and Ilaria have continued to work on the development of ground motion and seismic hazard models that can be used by stakeholders engaged in policy making and community-based risk reduction activities.

Susanne is also working with researchers from the University of Edinburgh, University College London and Kings College London on a multi-disciplinary research project designed to improve the assessment of time-independent and time-dependent seismic hazard in Yunnan and Sichuan in China, and how this kind of information is used by decision makers.

Richard Luckett and Brian Baptie are working with researchers at the University of Bristol on induced seismicity. Some of the results of this collaboration were published by Verdon et al (2017).

Richard and Brian are also working with physicists at National Physical Laboratory on the use of submarine optical cables for earthquake detection.

Brian Baptie is currently a Co-I of a new project, REMIS (Reliable Earthquake Magnitudes for Induced Seismicity). The project is funded by NERC (NE/R001154/1) and is a collaboration with the Universities of Leeds and Edinburgh. 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 conducting an independent environmental baseline monitoring programme in the Vale of Pickering, North Yorkshire.

BGS data are exchanged 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 424 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

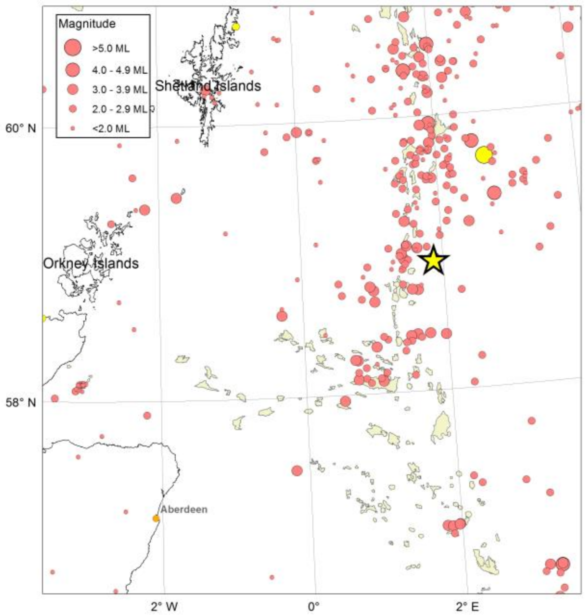
The details of all earthquakes, felt explosions and sonic booms detected by the BGS seismic network have been published in monthly bulletins and compiled in the BGS Annual Bulletins.

There were 218 local earthquakes located by the monitoring network during 2017-2018, with 26 having magnitudes of 2.0 ML or greater, and nine having magnitudes of 3.0 ML or greater. Fourteen events with a magnitude of 2.0 ML or greater were reported felt, together with a further 11 smaller ones, bringing the total to 25 felt earthquakes in 2017-2018.

The largest earthquake was a magnitude 4.7 ML event on 30 June 2017 in the central North Sea. The epicentre was 215 km southeast of Lerwick, Shetland and 310 km northeast of Aberdeen. It was felt in Shetland, Orkney, Wick, Thurso and in Fraserburgh with a maximum intensity of 3 EMS.

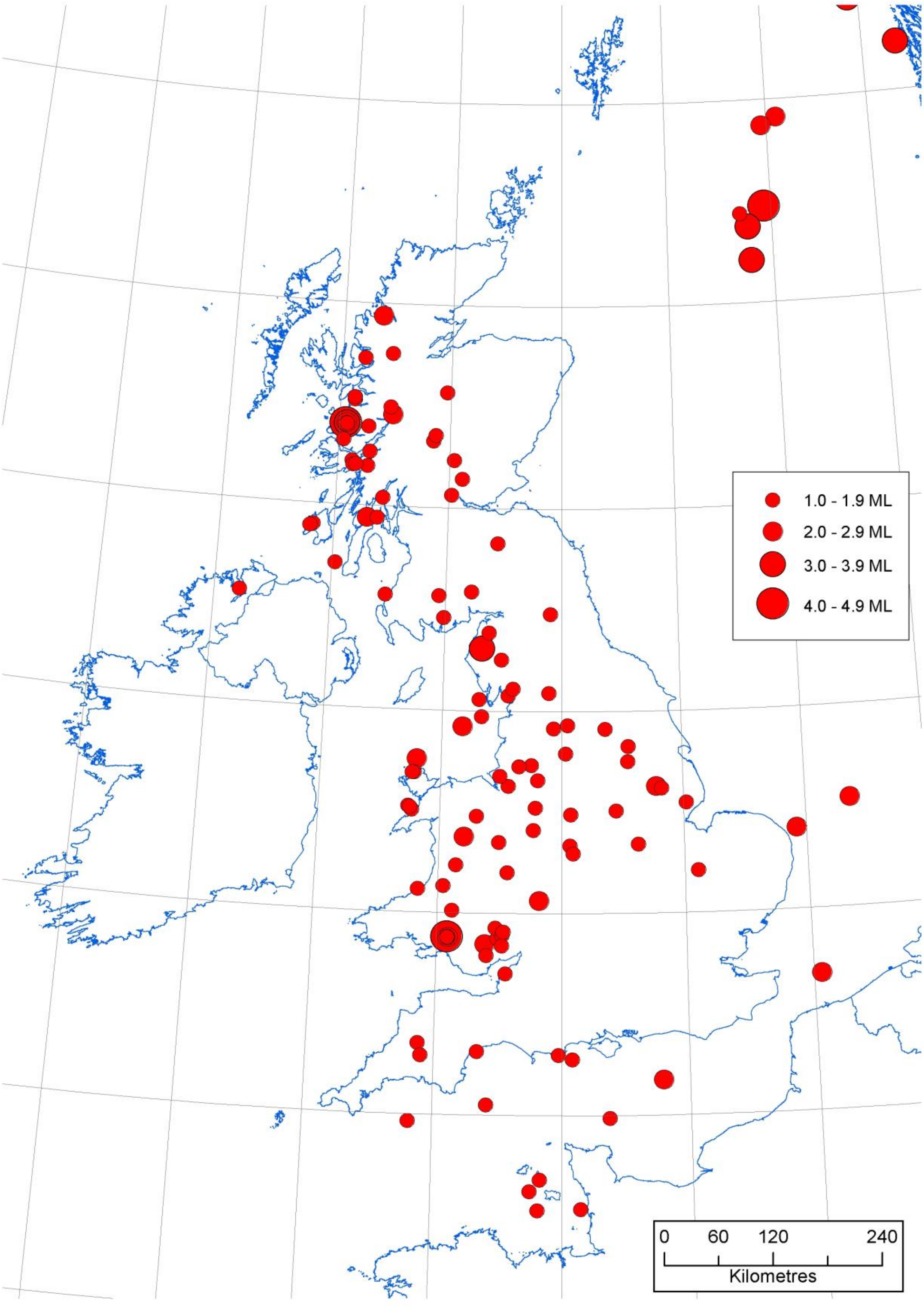
The South Wales earthquake of 17 February 2018 (4.6 ML) was the largest earthquake on mainland Britain in almost 10 years, since a magnitude 5.2 ML earthquake near Market Rasen on 27 February 2008. The epicentre was approximately 18 km north-northeast of Swansea but it was felt across all of Wales and much of England, with a maximum intensity of 5 EMS.

On 4 August 2017 at 14:43 UTC, an earthquake of magnitude 4.0 ML occurred in the locality of Moidart on the west coast of mainland Scotland. The epicentre was approximately 22 km south of Mallaig, 50 km west of Fort William and 145 km northwest of Glasgow. The earthquake was the largest event in the region since a magnitude 4.0 earthquake near Arran on 4 March 1999 that was felt widely across southwest Scotland.



Seismicity in the Central North Sea. Red circles show instrumentally recorded earthquakes from 1970 to present. Yellow circles show earthquakes prior to 1970. Circles are scaled by magnitude. The yellow star shows the epicentre of the magnitude 4.7 ML earthquake on 30 June 2017. Yellow shaded areas show oil fields.

A magnitude 3.4 ML earthquake occurred approximately 5 km south of Cockermouth, Cumbria, on 28 February. We received over 110 reports of the earthquake being felt, most of them from people living close to the epicentre and in the nearby towns of Whitehaven and Workington. The intensity of the shaking was generally weak or moderate. It was the largest earthquake in Cumbria since a magnitude 3.5 ML earthquake on 21 December 2010 near Coniston.



Epicentres of all earthquakes in and around the UK detected in the reporting period (1 April 2017 – 31 March 2018).

The Moidart Earthquake of 4 August 2017

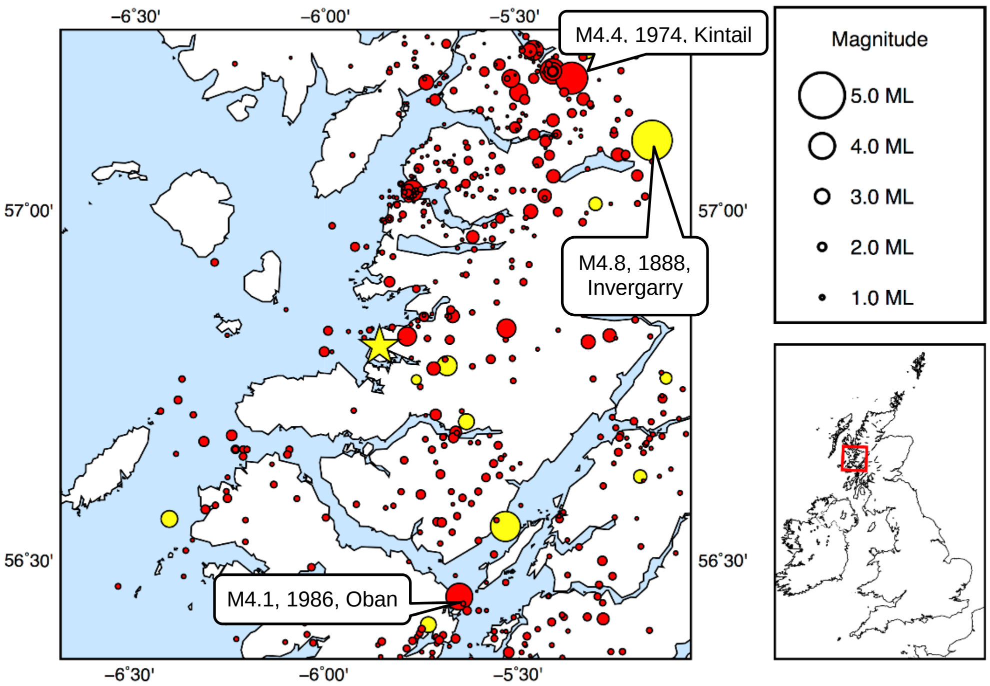
The Moidart earthquake of 4 August 2017 (4.0 ML) was the largest earthquake in Scotland for 18 years. The earthquake was felt widely across the west of Scotland. Only five other earthquakes of this size or greater have been observed in the period of instrumental recording from 1970 to present.

On 4 August 2017 at 14:43 UTC, an earthquake of magnitude 4.0 ML occurred in Moidart on the west coast of Scotland. The epicentre was approximately 22 km south of Mallaig, 50 km west of Fort William and 145 km northwest of Glasgow. The earthquake was the largest event in the region since a magnitude 4.0 earthquake near Arran on 4 March 1999 that was felt across southwest of Scotland.

The earthquake was followed by at least four aftershocks, the largest of which had a magnitude of 3.4 ML and which occurred two minutes after the mainshock. The two largest aftershocks were also felt.

Analysis of the BGS earthquake catalogue shows that there have been only five other earthquakes in this region with magnitudes of 4 ML or above in the period of instrumental monitoring from 1970 to present. The largest of these was a magnitude 4.4 ML earthquake near Kintail in 1974. This was one of a sequence of over 20 earthquakes that occurred over several months in 1974/1975. Two other earthquakes in this sequence also had magnitudes of above 4.0 ML. A magnitude 4.1 ML earthquake near Oban in 1986 was 24 km south-southeast of the Moidart earthquake.

Historical observations of earthquake activity in Scotland date back to the 16th

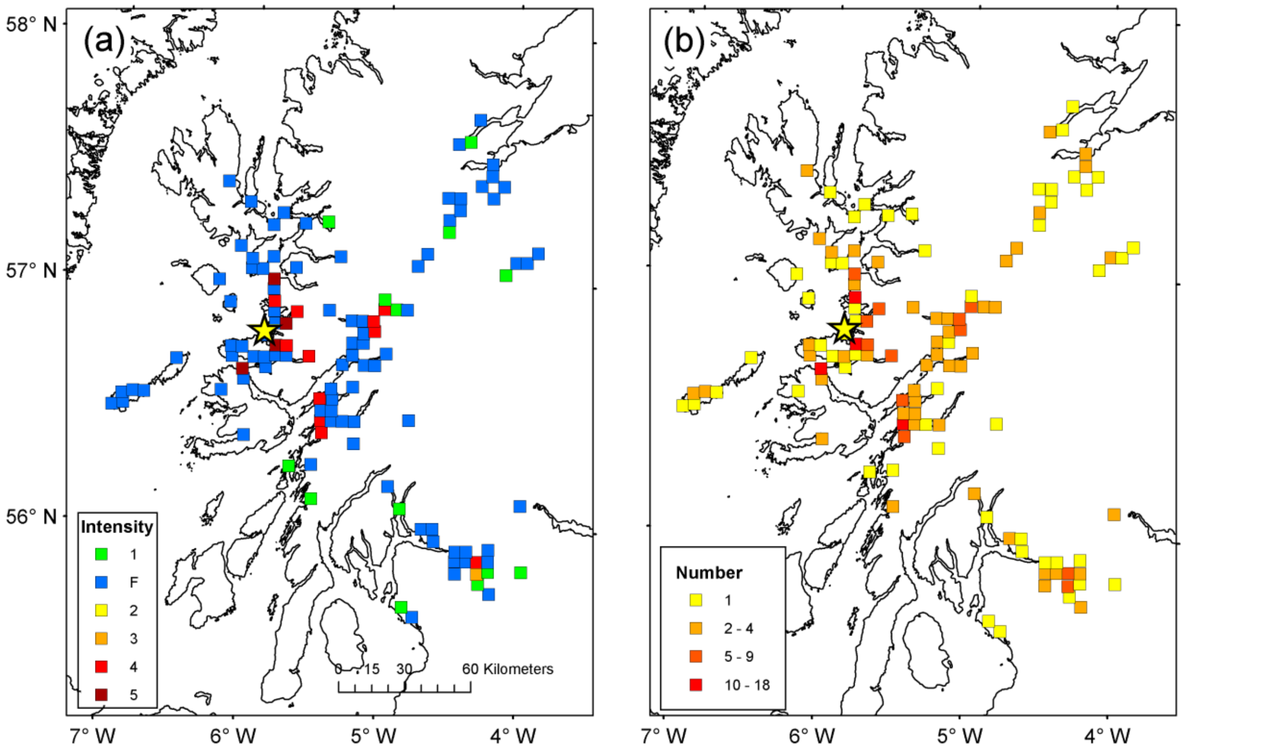


Instrumentally recorded earthquakes (red circles), from 1970 to present, and historical earthquakes (yellow circles), from 1700 to 1969, within a 100 km square centred on the epicentre of the Moidart earthquake of 4 August 2017 (yellow star). Circles are scaled by magnitude.

century (Musson, 1996). These show that despite many accounts of earthquakes felt by people, damaging earthquakes are relatively rare. Scotland's largest recorded earthquake, a magnitude 5.2 ML event in Argyll in 1880, was 75 km to the southeast of the Moidart earthquake. Only two other earthquakes with a magnitude of 5.0 ML or greater have been observed in the last 400 years.

Some 350 members of the public from 121 different postcodes completed our online questionnaire, allowing EMS intensities to be calculated in different locations. A minimum number of five reports from a given 5 km by 5 km square are required to estimate the intensity. Where there are fewer than 5 different observations, we assign an intensity value of “Felt”. A maximum intensity of 5 EMS was observed in the villages of Acharacle and Roshven, 10 km from the epicentre. An intensity of 5 EMS was also observed at Tobermory and Mallaig, approximately 20 km from the epicentre. Intensities of 4 EMS were observed at Lochailort (10 km), Strontian (12 km) and Arisaig (12 km). There were too few observations to determine a value for the intensity from most of the other locations close to the epicentre, perhaps as a result of the low population density. Intensities of 4 EMS were observed in Oban and Fort William at distances of 45 km to the southeast and 48 km to the east, respectively. The earthquake was felt at distances of up to 150 km from the epicentre, including Inverness and Invergarry to the northeast and Glasgow to the southeast. Five reports from central Glasgow suggest an intensity of 4 EMS, however, this does not seem consistent with other observations.

Over half of the reports state that people considered the shaking to be moderate in strength, while around one third thought that it was weak. Many people reported hearing a moderate to loud bang or rumble. There were 31 reports of objects falling over but no reports of damage.



Macroseismic intensities for the Moidart earthquake on 4 August 2017 (yellow star). Coloured squares in (a) show intensities calculated from macroseismic data. Blue 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.

Seismic Activity

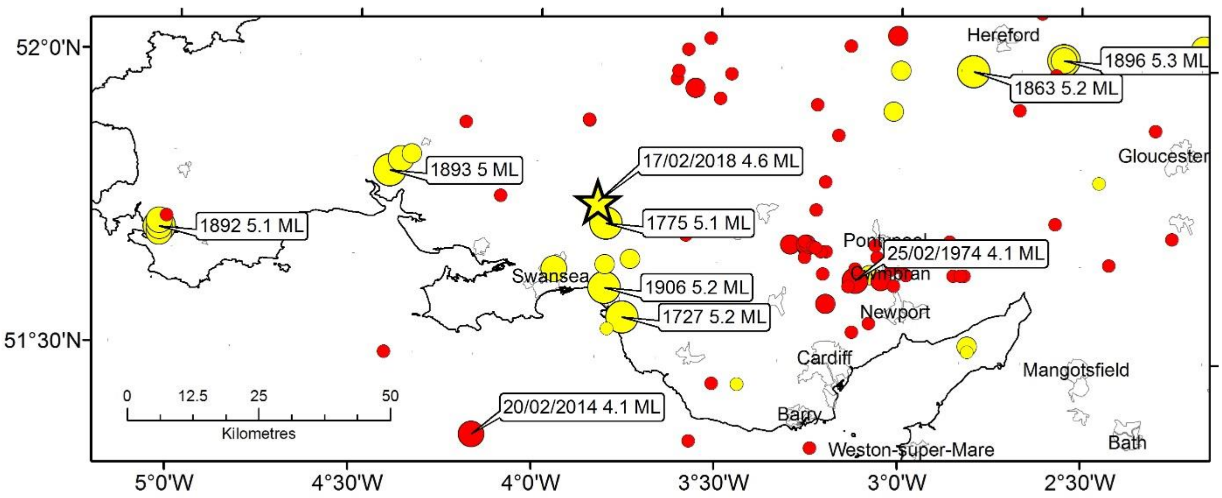
The South Wales Earthquake of 17 February 2018

The South Wales earthquake of 17 February 2018 (4.6 ML) was the largest earthquake on mainland Britain in almost 10 years, since a magnitude 5.2 ML earthquake near Market Rasen on 27 February 2008. The earthquake occurred in a part of South Wales that has experienced bursts of earthquakes with magnitudes of 5 ML or above at regular intervals in the last few hundred years, however, there has been relatively little seismicity in the region in the last few decades.

On 17 February 2018 at 14:31 UTC, a magnitude 4.6 ML earthquake occurred in South Wales. The epicentre was approximately 18 km north-northeast of Swansea and 55 km northwest of Cardiff, but it was felt across all of Wales and much of England. It was the largest earthquake on mainland Britain in almost 10 years, since the magnitude 5.2 ML Market Rasen earthquake on 27 February 2008 (Ottemöller and Sargeant, 2010).

The earthquake occurred in a part of South Wales that has been struck by a number of other significant earthquakes in the last few hundred years, although there has been relatively little seismicity in the last few decades. A magnitude 5.2 ML earthquake in 1906 was one of the most damaging British earthquakes of the 20th Century, with damage to chimneys and walls reported across South Wales (Davison, 1907). Earthquakes with magnitudes of 5.2 and 5.1 occurred near Swansea in 1727 and 1775, respectively. The epicentre of the earthquake on 17 February 2018 is close to the epicentre of the 1775 event.

More recently, a magnitude 4.1 ML



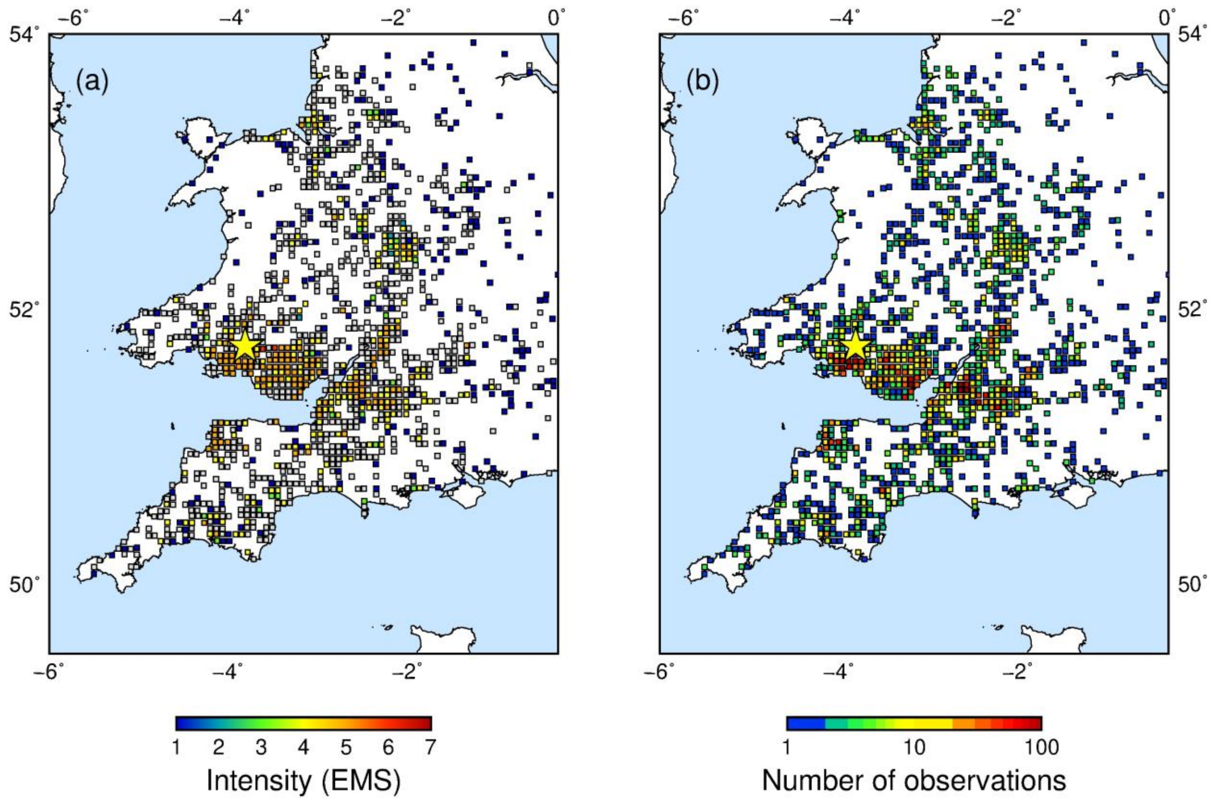
Instrumentally recorded earthquakes (red circles), from 1970 to present, and historical earthquakes (yellow circles), from 1700 to 1969, within a 200 km square centred on the epicentre of the South Wales earthquake of 17 February 2018 (yellow star). Circles are scaled by magnitude.

earthquake in the Bristol Channel on 20 February 2014, approximately 50 km to the southwest was also felt widely in South Wales. Three earthquakes with magnitudes of 4.1, 3.9 and 3.0 ML occurred in 1974, near Newport, approximately 50 km east. A cluster of instrumentally recorded seismicity approximately 40 km to the east, near Bargoed, may be associated with mining activity in the South Wales coalfields.

7811 members of the public completed our online macroseismic questionnaire. Data were grouped by postcode into 5 km by 5 km squares and an EMS (European Macroseismic Scale) intensity was calculated in each. We received data for 1363 different squares. An intensity of 5 EMS was reported widely throughout South Wales. An intensity of 5 EMS was also observed in North Devon (approximately 80 km); Bristol (100 km); Stroud, Gloucester and Cheltenham (approximately 120 km). Intensities of 4 EMS were observed at Swindon (145 km), Birmingham (155 km) and Liverpool (190 km). Reports are clearly biased towards areas of higher population density, with relatively few reports from Pembrokeshire or North Wales.

The earthquake was felt as far away as Blackpool, 240 km north-northeast of the epicentre; in the East Midlands, 200 km northeast; Oxford, 180 km east; Southampton, 200 km southeast; and as far east as Slough and Windsor, 225 km from the epicentre. The earthquake was also felt in much of Devon and Cornwall.

Over half of the reports (4543) stated that people considered the shaking to be moderate in strength, while 2833 reports stated that it was weak. The shaking was described as severe by 317 people. There were just over 200 reports of superficial damage, but on closer examination, many of these refer to existing cracks in plaster.



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. Yellow star denotes the epicentre.

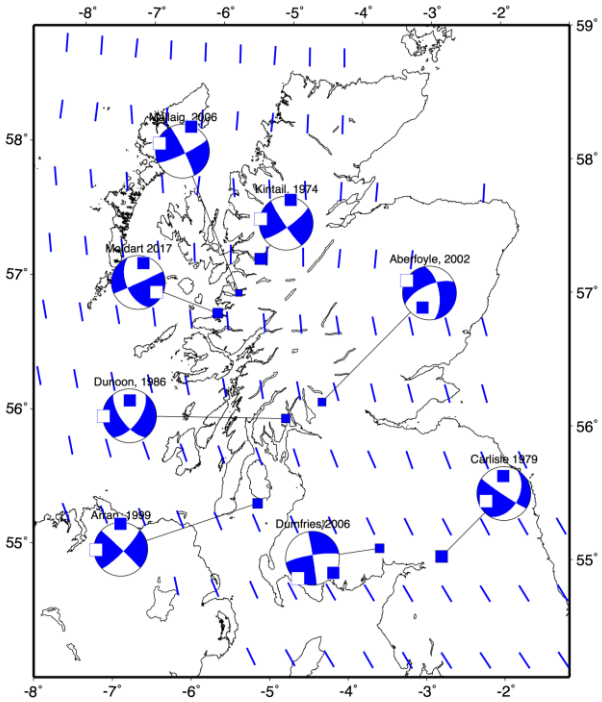
Research

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

Seismicity in northwest Scotland appears to be clustered around a number of large, steeply dipping major faults that strike either NE-SW or NW-SE suggesting that earthquake activity across the region is driven by reactivation of such fault systems by deformation associated with first-order plate motions rather than deformation associated with glacioisostatic recovery

A number of authors have suggested that the main cause for earthquake activity in northern Britain is deformation associated with glacio-isostatic recovery. This is 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.

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. For example, the Great Glen fault, the Strathconon fault and the Kinloch Hourn fault. Assumpçao (1981) suggests that the proximity of the hypocentre calculated for the 1974 Kintail earthquake to the Strathconon Fault, along with the agreement between the NE-SW strike of the fault and one of the calculated fault planes, provides evidence that the earthquake took place on this fault. Similarly, events such as the Oban earthquake of 1986 and the Inverness earthquakes in 1816, 1890 and 1901 could

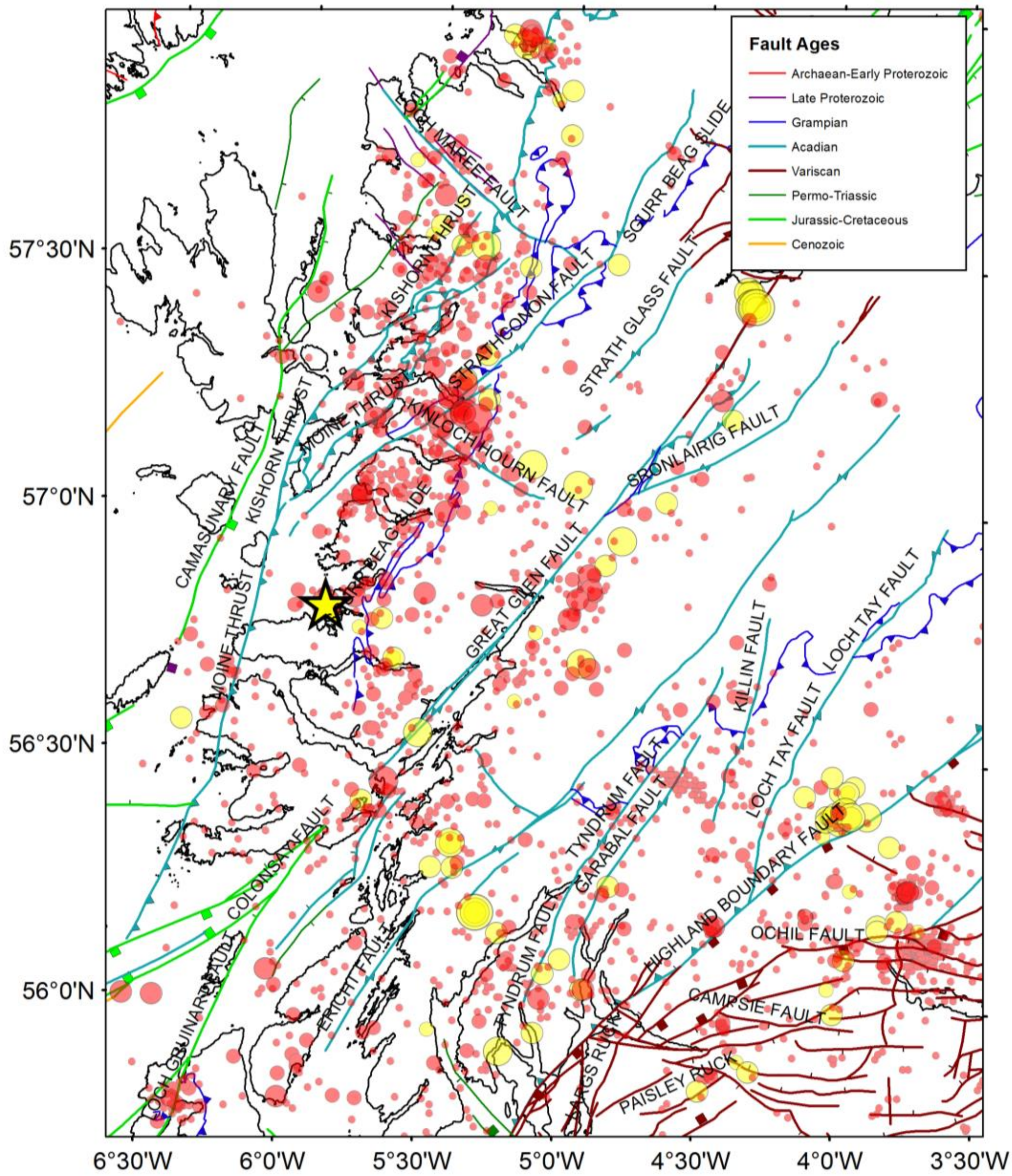


Focal mechanisms available for earthquakes in Scotland (Baptie, 2010). The lines between the quadrants show the strike and dip of the two possible fault planes. The axes of maximum and minimum compression are indicated by the blue and white squares respectively. The blue squares on the map show the location of the earthquakes. The blue lines show the orientation of the maximum horizontal compressive stress, sH (Heidbach et al., 2010).

be associated with reactivation of the Great Glen fault.

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 the 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.



Instrumentally recorded earthquakes (red circles), from 1970 to present, and historical earthquakes (yellow circles), from 1700 to 1969, in northwest Scotland. Circles are scaled by magnitude. The epicentre of the Moidart earthquake of 4 August 2017 is indicated by the yellow star. Lines show mapped faults from the British Geological Survey DigMapGB series, ©NERC 2016. The faults are coloured by geological age.

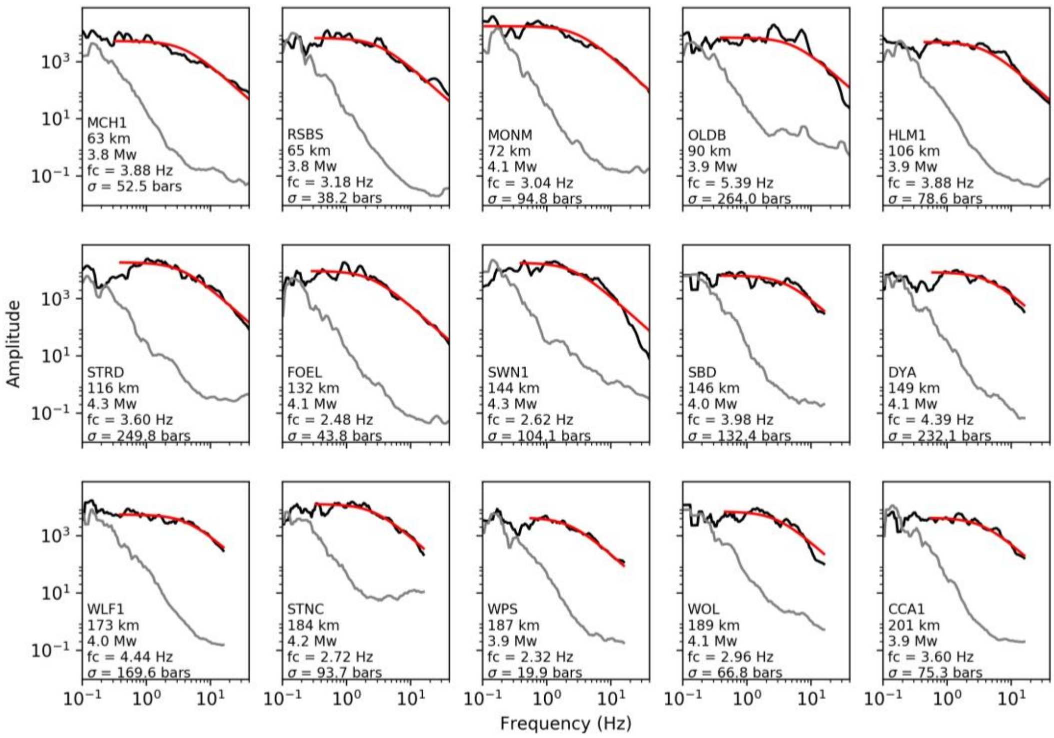
Research

Ground Motions for the South Wales Earthquake of 17 February 2018

We suggest that the large difference between the moment magnitude (4.0 ± 0.2 Mw) and the local magnitude (4.6 ± 0.4 ML) is a result of the relatively high stress drop for the earthquake. This also results in higher recorded peak ground accelerations for the earthquake than those predicted by commonly used ground motion prediction equations.

We determined a moment magnitude by modelling the source displacement spectra, using the spectral fitting method of Ottemöller and Havskov (2003), where the seismic moment, M_0, and the corner frequency, f_c, are determined using a grid search. A value of 4.0 ± 0.2 Mw was determined from the 15 observations. The spread in the moment magnitudes measured at each station is significantly less than for the measured local magnitudes. We find values for the source radius, *r*, and stress drop, Δσ, of 0.4 ± 0.1 km and 11.1 ± 7.8 MPa, respectively. The large uncertainty in the stress drop reflects the station-to-station variability of the corner frequency measurement.

The large difference between the moment magnitude and the local magnitude may be a result of the relatively high stress drop, since differences between moment and local magnitude have been observed from other high stress-drop intraplate earthquakes of a similar size (Carreno et al., 2008; Ottemöller and Sargeant, 2010).



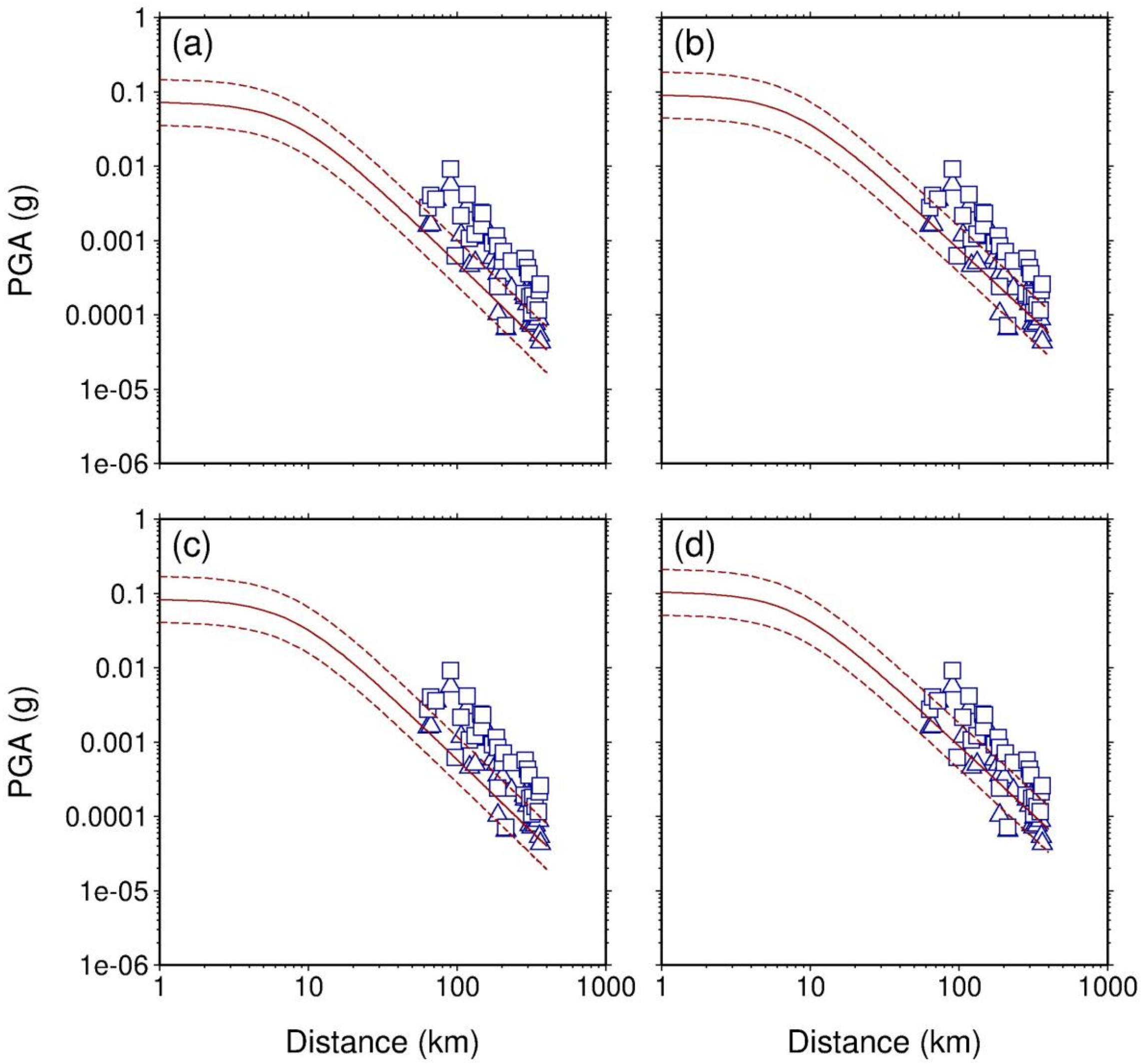
Observed displacement spectra (black) at the stations used to determine Mw. The red line shows the modelled displacement spectrum and the grey line shows the amplitude of the noise.

We measured peak ground accelerations (PGA) on all three component sensors at distances of up to 360 km from the epicentre. The maximum observed PGA is 9 cm/s^2 recorded at station OLDB (Oldbury), approximately 97 km from the epicentre.

We compare the observed PGA with PGA modelled with Akkar et al (2014) using moment magnitudes of 4.0 and 4.3 Mw for both a rock site and a soft rock site (NEHRP (US National Earthquake Hazards Reduction Program) classes B and C). In all four scenarios, we used a source depth of 7.5 km and strike-slip faulting.

For a magnitude of 4.0 Mw, on a rock site, most of the observations are outside the ±1σ bounds. Increasing the magnitude or changing the site conditions to NEHRP Class C improves the fit, but, in general, the GMPE still underestimates the observed PGA values. We repeated this analysis for two other GMPEs (Campbell and Borzognia, 2014; Chiou and Youngs, 2014) and find very similar results.

We suggest that the high stress drop may also result in higher recorded peak ground accelerations for the earthquake than those predicted by commonly used ground motion prediction equations used for seismic hazard assessments.



Peak ground accelerations (PGA) measured on three component sensors at distances of up to 360 km from the epicentre. Blue triangles show the vertical component of motion. Blue squares show the geometrical mean of the two horizontal components. The solid lines show PGA modelled with Akkar et al (2014) using: (a) a magnitude of 4.0 Mw at a rock site (NEHRP Class B); (b) a magnitude of 4.3 Mw at a rock site; (c) a magnitude of 4.0 Mw at a soft rock site (NEHRP Class C); (d) a magnitude of 4.3 Mw at a soft rock site. All four scenarios use a source depth of 7.5 km and strike slip faulting. The dashed lines show the uncertainty in the GMPE estimates (±1σ).

Research

Earthquake Triggering Potential

An investigation of links between subduction earthquakes in Mexico since 1978 (Segou and Parsons, 2018) suggests that the magnitude 8.1 Chiapas earthquake of 8 September 2017 did not trigger the magnitude 7.1 Puebla earthquake near Mexico City on 19 September 2017. Instead, extensive postseismic deformation following the magnitude 7.5 Oaxaca earthquake in 2012 appears to have critically stressed the Puebla rupture.

In September 2017, two damaging earthquakes hit Mexico posing the question: Are the two earthquakes linked? The first earthquake occurred offshore the state of Chiapas, in the southwest of Mexico on 8 September with a magnitude of 8.1. It was followed 11 days later by a magnitude 7.1 event in Puebla State in central Mexico. Although the latter was 600 km away from Mexico City, it caused significant casualties and major damage near the capital. It occurred during planned earthquake drills marking the anniversary of the devastating 1985 M8.0 Michoacan earthquake.

To answer the question about potential links between the two events, we investigated previous links between subduction earthquakes in Mexico since 1978 by assessing the dynamic and static triggering potential along this subduction zone. Our results show that the magnitude 8.1 Chiapas earthquake on 8 September did not trigger the magnitude 7.1 Puebla earthquake, rejecting the hypothesis of any link between them.

Looking back at the recent deformation history of the subduction zone on the Pacific coast of Mexico, we find that the extensive post-seismic deformation following the magnitude 7.5 Oaxaca earthquake in 2012 critically stressed the Puebla rupture. Similarly, we find that a magnitude 7.2 earthquake off the coast of southwest Mexico in 1993 was the most likely prompt for the magnitude 8.1 event on 8 September. We also find several other links during the past 40 years that repeat this pattern.

More generally, subduction zones worldwide pose a significant threat to coastal and other communities and megathrust-related events, such as the magnitude 9.0 Tohoku earthquake in 2011, are often characterized by complex deformation histories and intriguing patterns of coseismic slip at offshore locations.

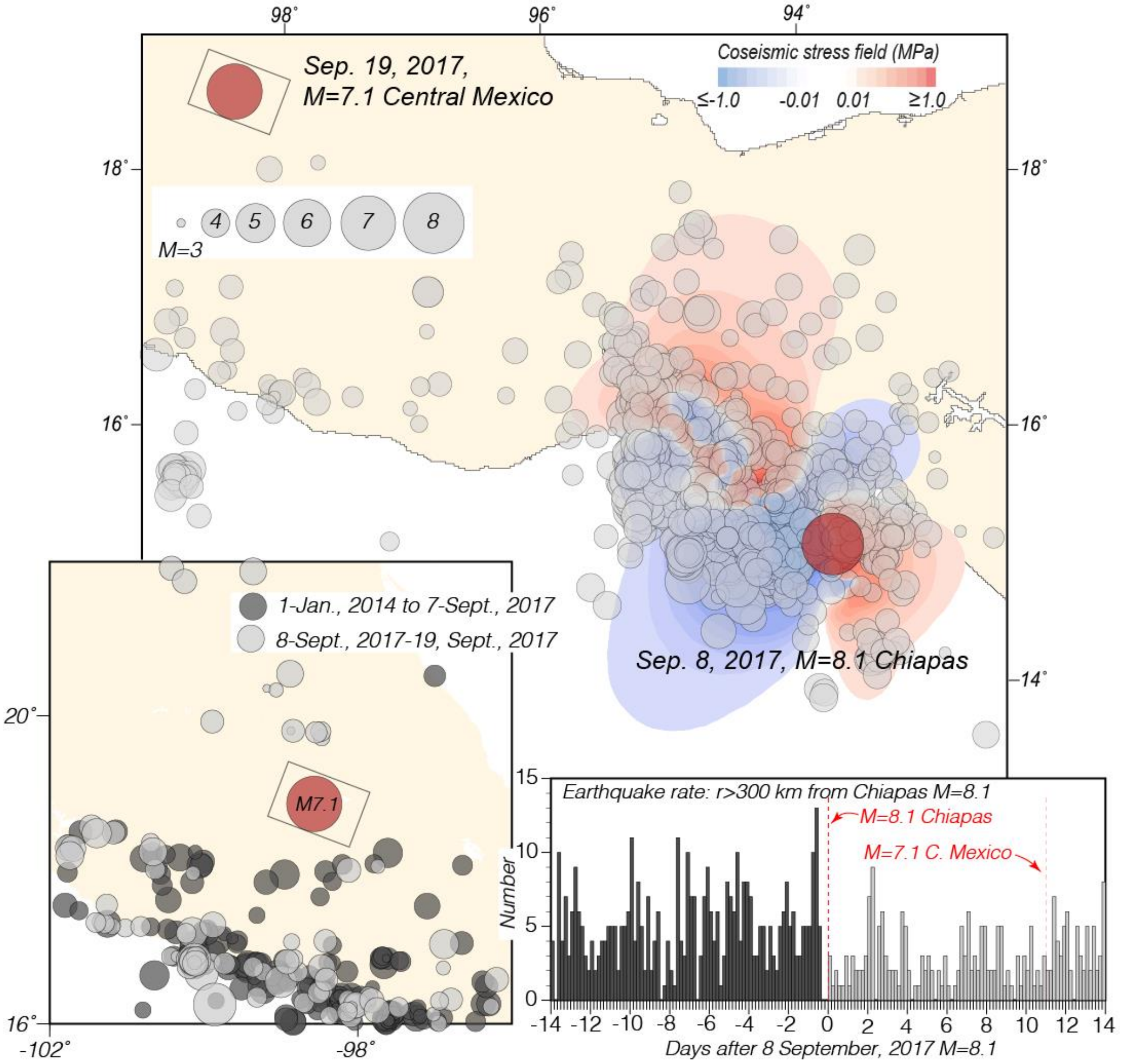
A recent collaboration between BGS and the Disaster Prevention Research Institute in Kyoto (Japan), funded by a RCUK-DPRI Kyoto Research Grant, has focused on an investigation of the Kumamoto earthquake sequence in Japan, in 2016. This study compared aftershock occurrence following both crustal and subduction events. The results show that local stress heterogeneity in Kyushu Island controls the geometry of aftershock ruptures.

A similar approach has been applied to the magnitude 7.2 Baja, California earthquake in 2010, which occurred at the continental collision between the America and Pacific tectonic plates near the well-known San

Andreas Fault. The results suggest that modelling elastic deformation at the time of the earthquake is not enough and in order to achieve a realistic Earth representation our geophysical parameters, such as principal stress axes, should include the pre-seismic history of the location.

These findings have significant implications for the previously long-standing approach to modelling stress changes, since our extensive statistical testing shows they perform poorly in comparison with the innovative total stress method.

In the future, we hope to extend the application of this approach and integrate it fully with rate-and-state models of aftershock forecasting in other high-seismic hazard locations of the world, focusing on big cities with high city growth rates.



Static and dynamic triggering potential from the M=8.1 Chiapas earthquake on 8 September 2017. The stress change caused by the earthquake does not reach the location of the Puebla rupture plane. Earthquakes following the 8 September event are plotted, with most clustering around that mainshock. Inset panels compare the locations and frequency of seismicity in the vicinity of the 19 September event; there was actually a reduction in the local earthquake rate, lending little support for a dynamic triggering response.

Research

Improving event detection and location

We have tested a number of automatic phase picking algorithms so that these can be included in our data acquisition to improve near real-time detection and location capability.

Very dense networks of seismic stations, such as that at the Vale-of-Pickering, that are designed to monitor very small earthquakes present a novel set of challenges in earthquake detection. For example: stations are often very close together, so noise may be coherent on several stations at once; separate phases may be very close together; the requirement to detect very small earthquakes means that the signal-to-noise ratio may be poor. In addition, earthquakes may occur in rapid succession during hydraulic fracturing, and these need to be located quickly and reliably to make effective operational decisions.

We have tested a number of automatic phase picking algorithms to assess their suitability for near real-time detection and location using a dense network. The algorithms that we tested are as follows: STA/LTA (Trnkoczy, 2012); Carltrig STA/LTA (Johnson et al., 1995); recursive STA/LTA (Withers et al., 1998); Z-Detect (Withers et al., 1998); Akaike Information Criterion (AIC), (Kitagawa and Akaike, 1978); the FBPicker (Lomax et al., 2012); and, the Kurtosis Picker (Saragiotis et al., 2002).

Each trigger has several parameters that need to be jointly optimised. This was done by trying many different combinations for each trigger and ranking them based on the number of known phases found, with some consideration to the number of false triggers.

We used 63 events from a sequence of over 300 mining induced earthquakes at Thoresby Colliery, New Ollerton (Verdon et al., 2017) to test the different detection algorithms. This gave a total of 362 manually picked P-wave arrival times on seven local stations.

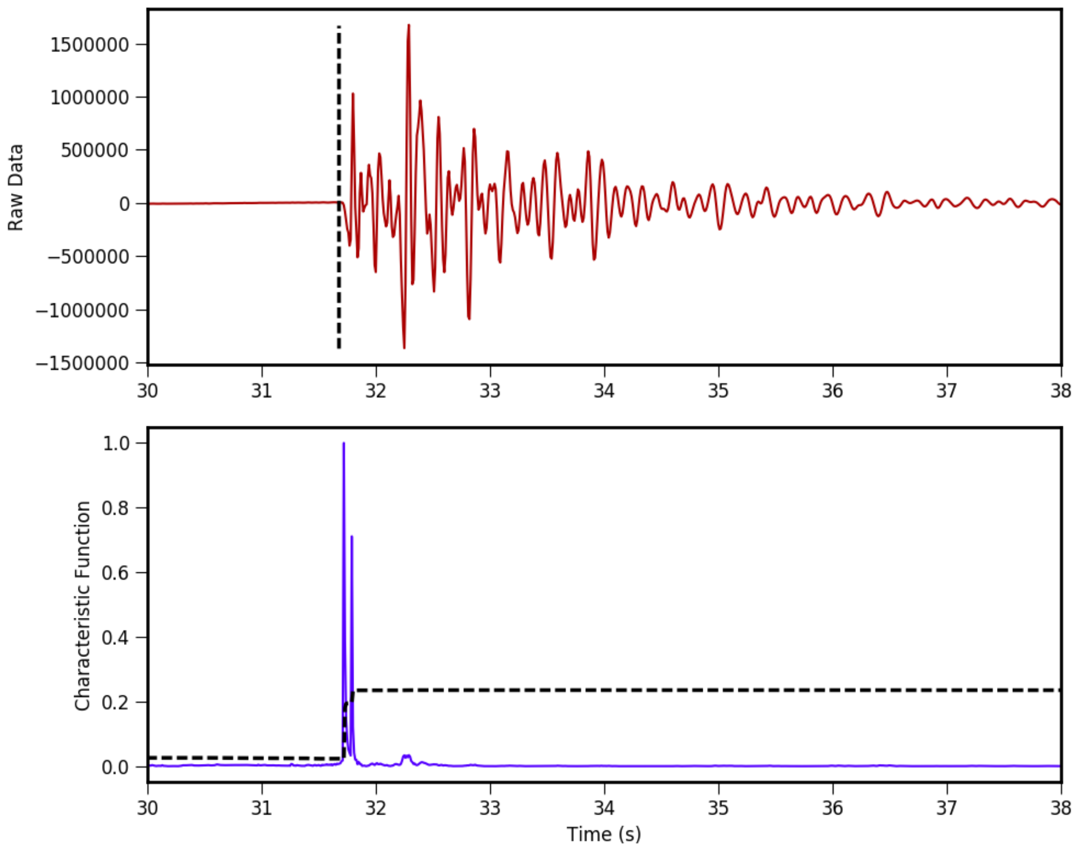
We tested each algorithm using only short windows of data around known events, rather than scanning long continuous records. This allowed us to check the accuracy of automatic picks by comparing them against manual picks, as well as to assess the number of missing and false

Algorithm	Number good	Number bad	Time per event
Basic STA/LTA	307	441	0.002 sec
Carltrig STA/LTA	299	154	0.3 sec
Recursive STA/LTA	335	40	0.001 sec
Z-detect	141	239	0.02 sec
AIC picker	312	41	6.5 sec
FBPicker	321	83	0.7 sec
Kurtosis picker	315	48	12.6 sec

Summary results of testing the different detection algorithms.

detections. We consider a pick good if it is within 1 second of the manual pick for that station. Picks made more than 1 second from a manual pick were considered ‘bad’. We also consider the time taken for the algorithm to scan the data for each event.

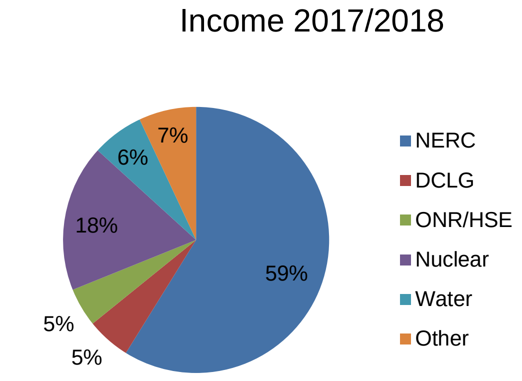
Apart from the Z-detect algorithm, all of the pickers detected more than 80% of the picks found for these events manually. This means that, they would have detected all of the events if three station triggers were required for a detection. However, we find significant differences in the number of bad picks and in the time taken to calculate the characteristic function. The latter is an important consideration for real-time detection and location, and both the AIC picker and the Kurtosis pickers are unsuitable for real-time processing for this reason. The number of bad picks is important because too many bad station picks increase the chance of false event triggers significantly. Both the basic STA/LTA and the Carltrig STA/LTA have many more bad picks and so are not as good a choice. This leaves the FBPicker as implemented by Lomax et al. (2012) and the recursive STA/LTA. The latter was quicker for this test and found slightly more good picks and slightly less bad ones. The difference is not significant but this algorithm is also very simple to implement and is the algorithm chosen to carry forward to the next step, which is automatic event location.

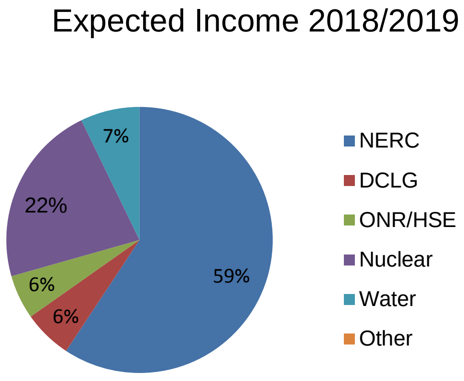


Traces showing the action of the FBPICK algorithm. The top trace is the unfiltered vertical waveform for station NOLA of the New Ollerton temporary network. The event is a magnitude 2 ML mining induced earthquake at 16:01 on 13/2/2014. The second trace shows the characteristic function generated by the algorithm. The black dashed line is the status of the trigger. The vertical line on the top trace shows where the trigger status crosses a set threshold and a pick is declared.

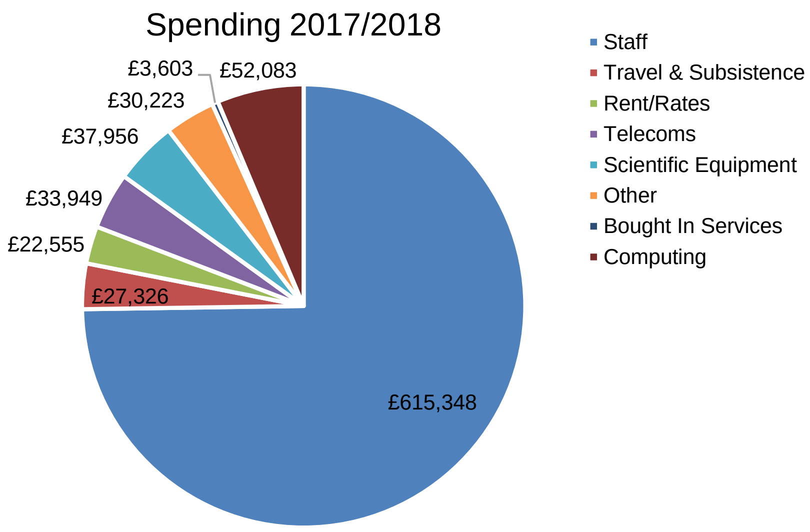
Funding and Expenditure

In 2017-2018 the project received a total of £734K, including a contribution of £464K from NERC. This was matched by a total contribution of £270K from the customer group drawn from industry, regulatory bodies and central and local government. The funding we receive from government, currently via NERC, is increasingly targeted. The reduction in NERC funding is primarily a consequence of specific targeting on Official Development Assistance (ODA). However, in 2017/2018 we were also awarded £57K for ODA projects.





The projected income for 2018-2019 is slightly less than that received in 2017-2018, mainly as a result in further reductions in NERC funding. This reflects a reduction in NERC funding for BGS in general. The NERC contribution for 2018-2019 currently stands at £420K, but we hope to increase this through applications for additional funding through the year. The total expected customer group contribution currently stands at £289K. We have also been awarded £111K for ODA projects.



Total spending in 2017/2018 was approximately £830k, slightly more than the project income.

Acknowledgements

This work would not be possible without the continued support of the Customer Group. The current members are as follows: the Department for Communities and Local Government, EDF Energy, Horizon Nuclear Power, Jersey Water, Magnox Ltd., the Office for Nuclear Regulation, Sellafield Ltd, Scottish Power, Scottish Water and SSE. 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 and this report is published with the approval of the Director of the British Geological Survey (NERC).

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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., Ford, G. and Galloway, D., 2017. The Moidart earthquakes of 4 August 2017, British Geological Survey Open Report, OR/17/062.

Baptie, B., Ford, G. and Galloway, D. 2018. The South Wales earthquake of 17 February 2018. British Geological Survey Open Report, OR/18/019.

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Zhao, Y., Curtis, A., and Baptie, B., 2017. Locating micro-seismic sources with a single seismometer channel using coda wave interferometry. Geophysics, 82(3).

Appendix 3 Publication Summaries

The Moidart earthquakes of 4 August 2017

B Baptie, G Ford, D Galloway

The Moidart earthquake of 4 August 2017 (4.0 ML) was the largest earthquake in Scotland for 18 years. The earthquake was felt widely across the west of Scotland. Only five other earthquakes of this size or greater have been observed in the period of instrumental recording from 1970 to present. Historical observations and instrumental recordings have been used to estimate that an earthquake of 4.0 ML or greater occurs somewhere in Scotland roughly every 8-9 years on average. The earthquake hypocentre was calculated using an iterative linearized method. The results suggest that the earthquake occurred in the mid-Crust at a depth of approximately 12 km. This is largely consistent with observed focal depths for other earthquakes in the region, which are distributed throughout the upper 20 km of the Crust. The strong similarity between the recorded ground motions from the mainshock and the four recorded aftershocks suggests that they all occurred within a small source volume, of the order of a few hundred metres in extent and had similar source mechanisms. The modelled source displacement spectra provide a good fit for the observed displacement spectra and suggest a moment magnitude (Mw) of 3.6 ± 0.1. This is slightly less than that expected for an earthquake with a local magnitude of 4.0 ML using commonly used empirical relationships relating local and moment magnitude, which gives an expected moment magnitude of 3.7. The calculated focal mechanism suggests that the earthquake resulted from strike-slip faulting on a fault plane that strikes either SW-NE or NW-SE and dips steeply, although the dip of both fault planes is rather poorly constrained. This is in good agreement with focal mechanisms calculated for other earthquakes across the region, which all show similar solutions. Seismicity in northwest Scotland is clustered around a number of large, steeply dipping major faults that strike either NE-SW or NW-SE suggesting that earthquake activity across the region is driven by reactivation of such fault systems by deformation associated with first-order plate motions rather than deformation associated with glacioisostatic recovery. Although there are no mapped major fault systems in the immediate vicinity of the Moidart earthquake, it seems likely that the earthquake also occurred on a steeply dipping fault that strikes either NE-SW or NW-SE but remains unmapped.

The South Wales earthquake of 17 February 2018

B Baptie, G Ford, D Galloway, 2018.

The South Wales earthquake of 17 February 2018 (4.6 ML) was the largest earthquake on mainland Britain in almost 10 years, since a magnitude 5.2 ML earthquake near Market Rasen on 27 February 2008. The earthquake occurred in a part of South Wales that has experienced bursts of earthquakes with magnitudes of 5 ML or above at regular intervals in the last few hundred years, which may suggest that seismicity in this region is highly clustered in both space and time. However, there has been relatively little instrumentally recorded seismicity in the region in the last few decades. The epicentre of the earthquake on 17 February 2018 is close to the estimated epicentres of three earthquakes with magnitude greater than 5 ML in 1727, 1775 and 1906. We determined a hypocentre and source mechanism for the South Wales earthquake using P- and S-wave arrival times measured from instrumental recordings. The distribution of stations means that the error in the earthquake epicentre is less than 2.5 km. The focal depth of 7.5 km suggests that the earthquake may have nucleated at a relatively shallow depth. However, the error in the calculated depth is ±9.3 km, as the closest seismometer that recorded the earthquake was at a distance of 63 km. The calculated focal mechanisms show a near vertical, strike slip fault, with either left-lateral slip on a fault that strikes NE or right lateral slip on a fault that strikes NW. Neither of these is a good match for observed surface faulting near the epicentre. However, the NW plane is good match to the strike of the main Variscan Thrust, which cuts through the region. The NE plane is a reasonable match to the Acadian age faults that are observed at the surface to the north of the epicentre We suggest that the large difference between the moment magnitude (4.0 ± 0.2 Mw) and the local magnitude (4.6 ± 0.4 ML) is a result of the relatively high stress drop for the earthquake. This also results in higher recorded peak ground accelerations for the earthquake than those predicted by commonly used ground motion prediction equations used for seismic hazard assessments. Moment magnitudes measured at individual stations show considerably less scatter than local magnitude measurements, suggesting that the former are less dependent on site effects. We also observe that the stress drops calculated at each station increase with the local magnitude calculated at that station.

The Bulletin of British Earthquakes 2016.

D. Galloway

The British Geological Survey's (BGS) Seismic Monitoring and Information Service operate 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 2016, listed in Tables 1 and 2. Maps showing seismic activity in 2016 (Figure 1), 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 (11°W to 6°E and 47°N to 65°N). All events believed to be of true tectonic origin are included. Coalfield events are also included. Acoustic disturbances, such as sonic booms from supersonic aircraft, are included when they are felt. The airborne waves are readily identified by their slow travel time across an array or by their signature on a microphone, but they are frequently mistaken as small earthquakes by the public. They are indicated by 'SONIC' in both the locality and comments column of Table 1. Significant non-natural events, such as explosions, which received media attention or were greater than magnitude 2.5 ML or felt by local residents, are also included in Table 1. Smaller events that are known, or suspected to be of explosive origin are excluded from the bulletin where possible. These include explosions due to quarrying, mining, weapon testing or disposal, naval exercises, geophysical prospecting and civil engineering. Unfortunately, identification by record character, location and time of occurrence is not always conclusive and some man-made events may be included in the bulletin or, more rarely, a small natural event may have been excluded.

Testing Earthquake Links in Mexico From 1978 to the 2017 M = 8.1 Chiapas and M = 7.1 Puebla Shocks

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The M = 8.1 Chiapas and the M = 7.1 Puebla earthquakes occurred in the bending part of the subducting Cocos plate 11 days and ~600 km apart, a range that puts them well outside the typical aftershock zone. We find this to be a relatively common occurrence in Mexico, with 14% of M > 7.0 earthquakes since 1900 striking more than 300 km apart and within a 2 week interval, not different from a randomized catalog. We calculate the triggering potential caused by crustal stress redistribution from large subduction earthquakes over the last 40 years. There is no evidence that static stress transfer or dynamic triggering from the 8 September Chiapas earthquake promoted the 19 September earthquake. Both recent earthquakes were promoted by past thrust events instead, including delayed afterslip from the 2012 M = 7.5 Oaxaca earthquake. A repeated pattern of shallow thrust events promoting deep intraslab earthquakes is observed over the past 40 years.

Seismicity induced by longwall coal mining at the Thoresby Colliery, Nottinghamshire, U.K.

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The United Kingdom has a long history of deep coal mining, and numerous cases of mining-induced seismicity have been recorded over the past 50 yr. In this study, we examine seismicity induced by longwall mining at one of the United Kingdom’s last deep coal mines, the Thoresby Colliery, Nottinghamshire. After public reports of felt seismicity in late 2013 a local seismic monitoring network was installed at this site, which provided monitoring from February to October 2014. This array recorded 305 seismic events, which form the basis of our analysis.

Event locations were found to closely track the position of the mining face within the Deep Soft Seam, with most events occurring up to 300 m ahead of the face position. This indicates that the seismicity is being directly induced by the mining, as opposed to being caused by activation of pre-existing tectonic features by stress transfer. However, we do not observe correlation between the rate of excavation and the rate of seismicity, and only a small portion of the overall deformation is being released as seismic energy.

Event magnitudes do not follow the expected Gutenberg–Richter distribution. Instead, the observed magnitude distributions can be reproduced if a truncated power-law distribution is used to simulate the rupture areas. The best-fitting maximum rupture areas correspond to the distances between the Deep Soft Seam and the seams that over- and underlie it, which have both previously been excavated. Our inference is that the presence of a rubble-filled void (or goaf) where these seams have been removed is preventing the growth of larger rupture areas.

Source mechanism analysis reveals that most events consist of dip-slip motion along near-vertical planes that strike parallel to the orientation of the mining face. These mechanisms are consistent with the expected deformation that would occur as a longwall panel advances, with the under- and overburdens moving upwards and downwards respectively to fill the void created by mining. This further reinforces our conclusion that the events are directly induced by the mining process. Similar mechanisms have been observed during longwall mining at other sites.

Locating microseismic sources with a single seismometer channel using coda wave interferometry

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A novel source location method based on coda wave interferometry (CWI) was applied to a microseismic data set of mining-induced events recorded in Nottinghamshire, England. CWI uses scattered waves in the coda of seismograms to estimate the differences between two seismic states. We used CWI to estimate the distances between pairs of earthquake locations, which are then used jointly to determine the relative location of a cluster of events using a probabilistic framework. We evaluated two improvements to this location technique: These account for the impact of a large difference in the dominant wavelength of a recording made on different instruments, and they standardize the selection of parameters to be used when implementing the method. Although the method has been shown to produce reasonable estimates on larger earthquakes, we tested the method for microseismic events with shorter distinguishable codas in recorded waveforms, and hence, fewer recorded scattered waves. The earthquake location results are highly consistent when using different individual seismometer channels, showing that it is possible to locate event clusters with a single-channel seismometer. We thus extend the potential applications of this cost-effective method to seismic events over a wider range of magnitudes.

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