British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Earthquake Seismology 2016/2017

BGS Seismic Monitoring and Information Service

Twenty-eighth Annual Report

BRITISH GEOLOGICAL SURVEY

OPEN REPORT OR/17/033

Earthquake Seismology 2016/2017

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Installing a borehole sensor in the Vale of Pickering, Yorkshire.

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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 near-immediate responses 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 28th 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. Four presentations were made at international conferences. Five BGS reports were prepared along with three external reports. We have continued to collaborate widely with academic partners across the UK and overseas on a number of research initiatives.

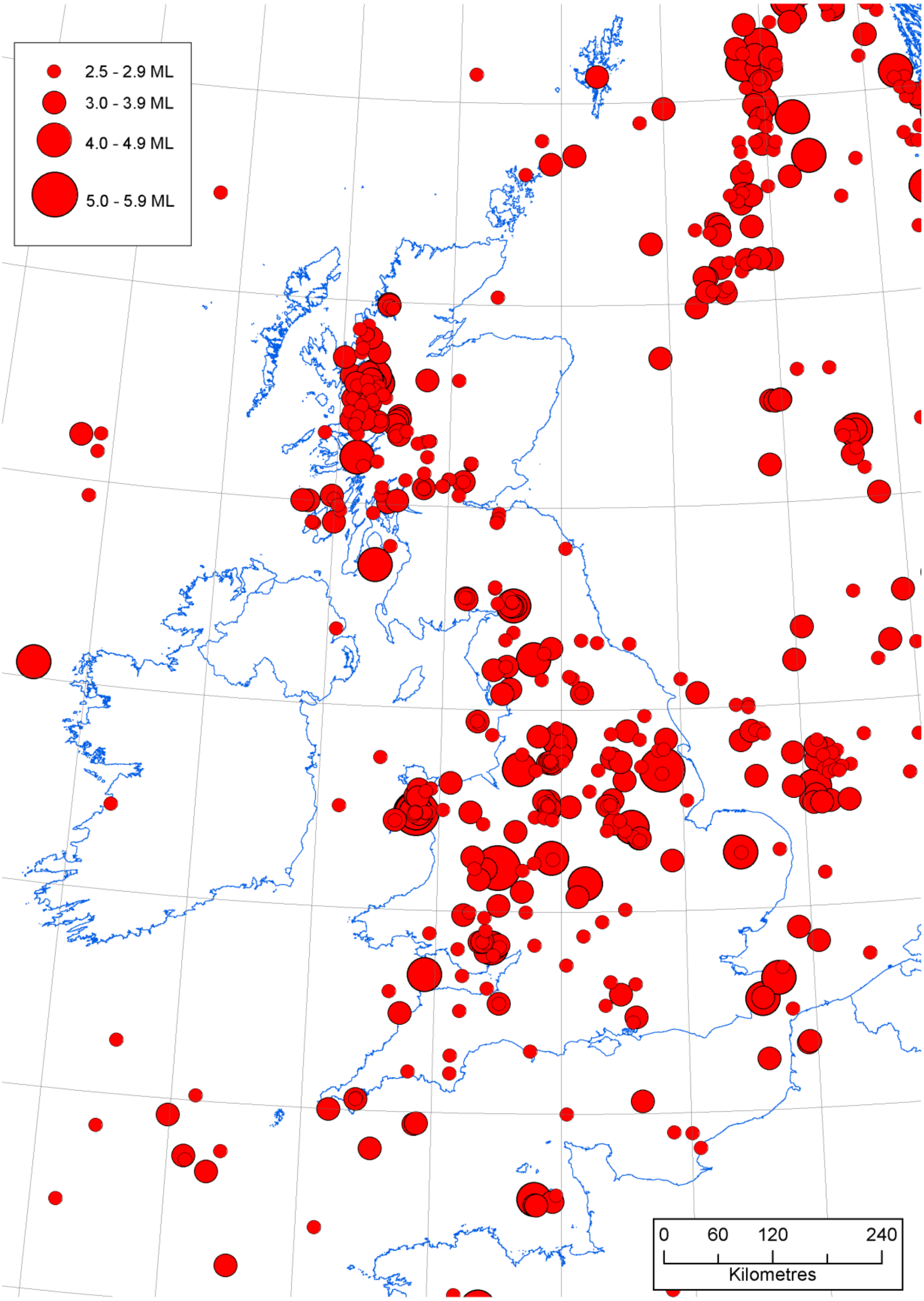
Introduction

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.

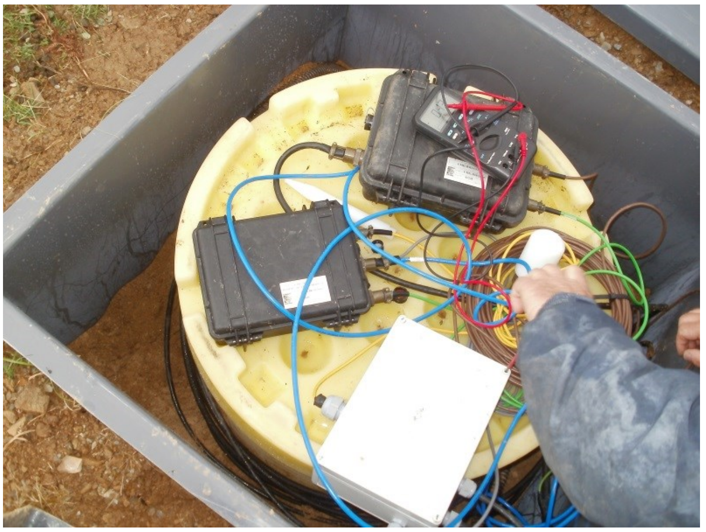
Almost every week, seismic events are reported to be felt somewhere in the UK. A small number of these prove to be sonic booms or are spurious, but a large proportion are natural or mining-induced earthquakes often felt at intensities which cause concern and, occasionally, some damage. The Information 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 M_L. 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 M_L. 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 2017.



Monitoring Network

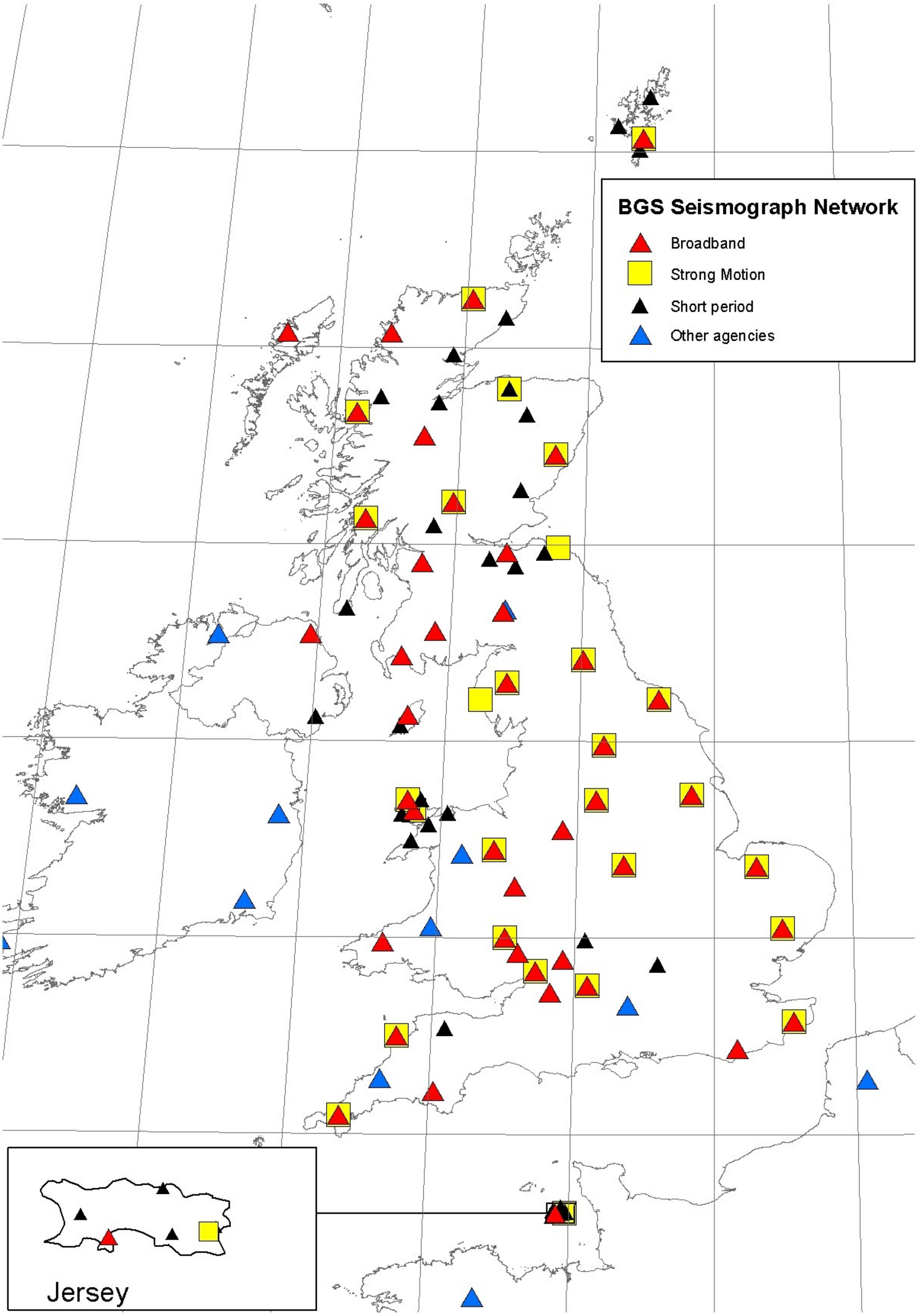
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late 1990s, the number of stations reached its peak of 146, with an average spacing of 70 km. We are now in the process of a major upgrade, with the installation of broadband seismometers that will provide 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.

This year we have continued to develop the monitoring network, to provide high quality, near real-time data. So far, we have installed 44 broadband sensors at stations across the UK along with 30 strong motion accelerometers with high dynamic range for recording very large signals.



BGS seismograph stations, March 2017

Achievements

Network Performance

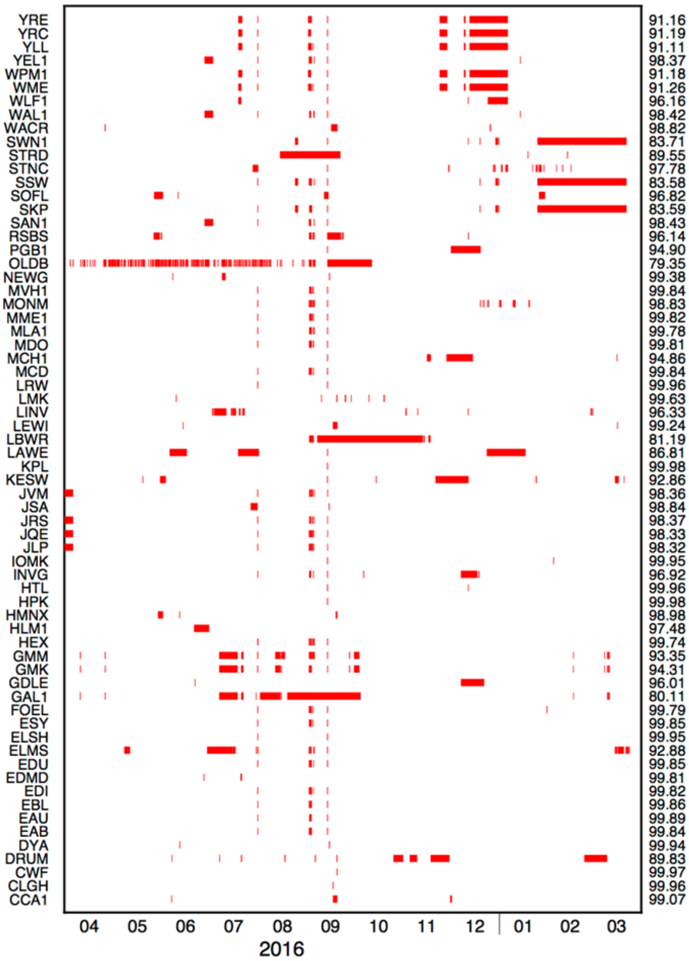
The network contains 44 broadband sensors with 24-bit acquisition which provide real-time data from across the UK. We continue to improve our near real-time data processing capability including the detection and location of significant seismic events in the UK and offshore area.

The network currently consists of 44 broadband sensors, 30 strong motion sensors and 29 short period sensors. In the last year the broadband station near Bath was decommissioned. Continuous data from all stations are transmitted in real-time to Edinburgh, where they are used for analysis and archived.

We have continued to incorporate data from seismic stations operated by European partner agencies into our near real-time processing to improve our detection capability in offshore areas. In particular, stations operated by the AWE Blacknest and the Dublin Institute of Advanced Studies, in Ireland, are vital for detection and location in a number of areas, e.g. the Irish Sea.

During the year, a total of 44 field trips were made to visit 123 sites around the UK taking a total of 241 person days. Of these visits, 41 were for maintenance or fault repair, four were to carry out site surveys for new stations, five were for installation of new stations and two were for decommissioning of old stations.

Continuous data from all our stations are archived within the BGS storage area network. The completeness of these data can be easily checked to gain an accurate picture of network performance. For 2016-2017, data are more than 95% complete 70% of the time, 90% complete 86% of the time, 85% complete 90% of the time and 80% complete 98% of the time, which is a significant improvement on the previous year when data was

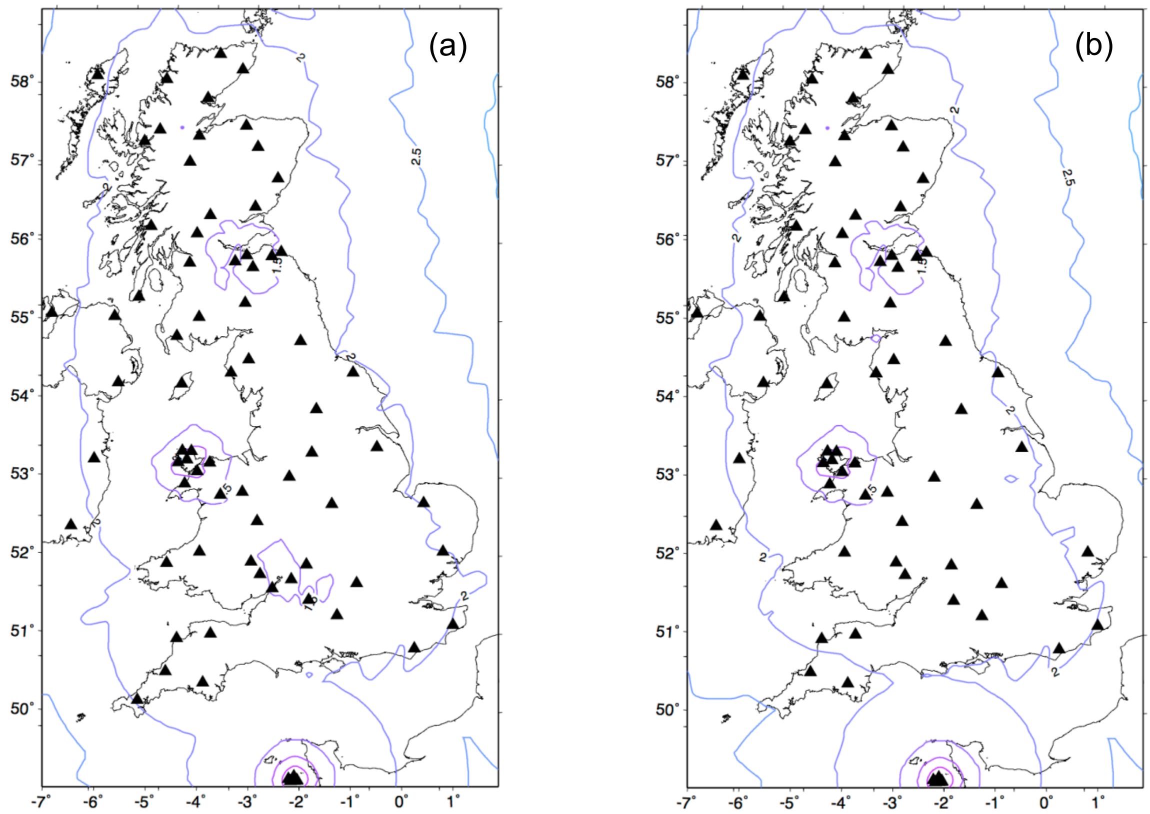


Data completeness for all broadband stations that operated throughout 2016/2017. Data are more than 95% complete 70% of the time, 90% complete 86% of the time, 85% complete 90% of the time and 80% complete 98% of the time.

80% complete for more than 90% of stations and more than 90% complete for over 60% of stations. Data losses result from failure of outstation hardware, communications problems, or failure of central data processing. The data acquisition is able to recover from short breaks in communications links to outstations by re-requesting missing packets of data from local data buffers, but failure of outstation hardware requires intervention by local operators or maintenance visits.

The worst performing stations were OLDB, Oldbury (79%), GAL1, Galloway (80%), LBWR, Ladybower (81%) and SWN1, Swindon (83%). In the case of Oldbury much of the loss of data resulted from a highly unreliable communications link. This was repaired in October 2016. Loss of data at the other three resulted from equipment failure that was concurrent with communications failures.

In addition, fewer than five stations were down 70% of the time and less than ten down 90% 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 September 2016, six stations (WACR, STRD, GAL1, LBWR, CCA1 and RSBS were down at the same time. This does not have a significant effect on overall detection capability except on the east coast of England around Suffolk and Norfolk and Lincolnshire.



Detection capability of the network with (a) all stations operational (b) six stations 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.

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.

Installing a borehole sensor near Kirby Misperton in the Vale of Pickering. A total of four borehole sensors were installed to improve detection capability.

We have installed eleven stations in the Vale of Pickering and a further six stations in Lancashire in the Bowland Basin, which is another area of shale gas potential. A further eight stations have been installed more widely across the north of England and we plan to install a further 21 stations over the next year.

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.

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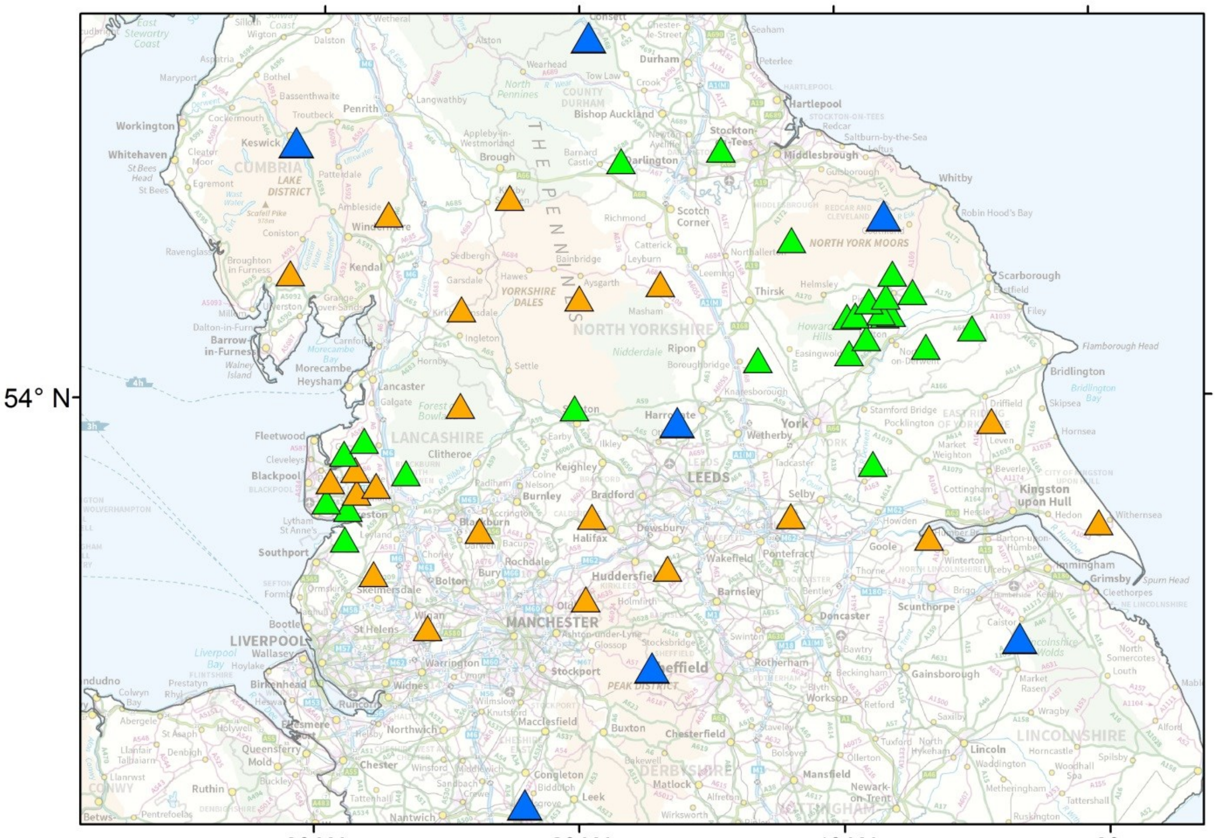


The development of the seismic network in the North of England as a result of the UKArray experiment and the Environmental Baseline Monitoring project in the Vale of Pickering. Blue triangles show permanent stations. Green triangles shows stations installed over the last two years. Orange triangles show approximate locations for planned stations.

Achievements

Information Dissemination

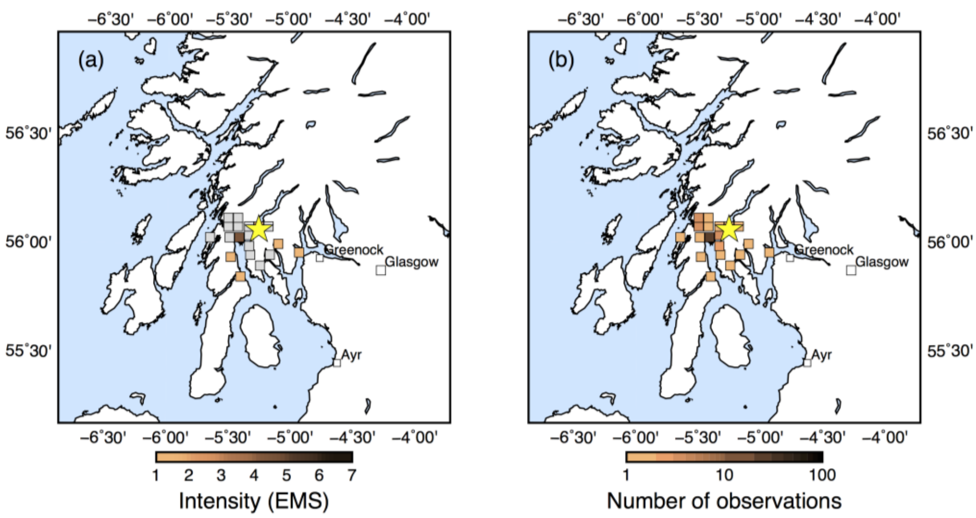
It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received notification by e-mail whenever an event was felt or heard by more than two individuals.

Notifications were issued for 17 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. Seven of the alerts were for earthquakes on mainland Britain and a further eight 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 2016 to March 2017.

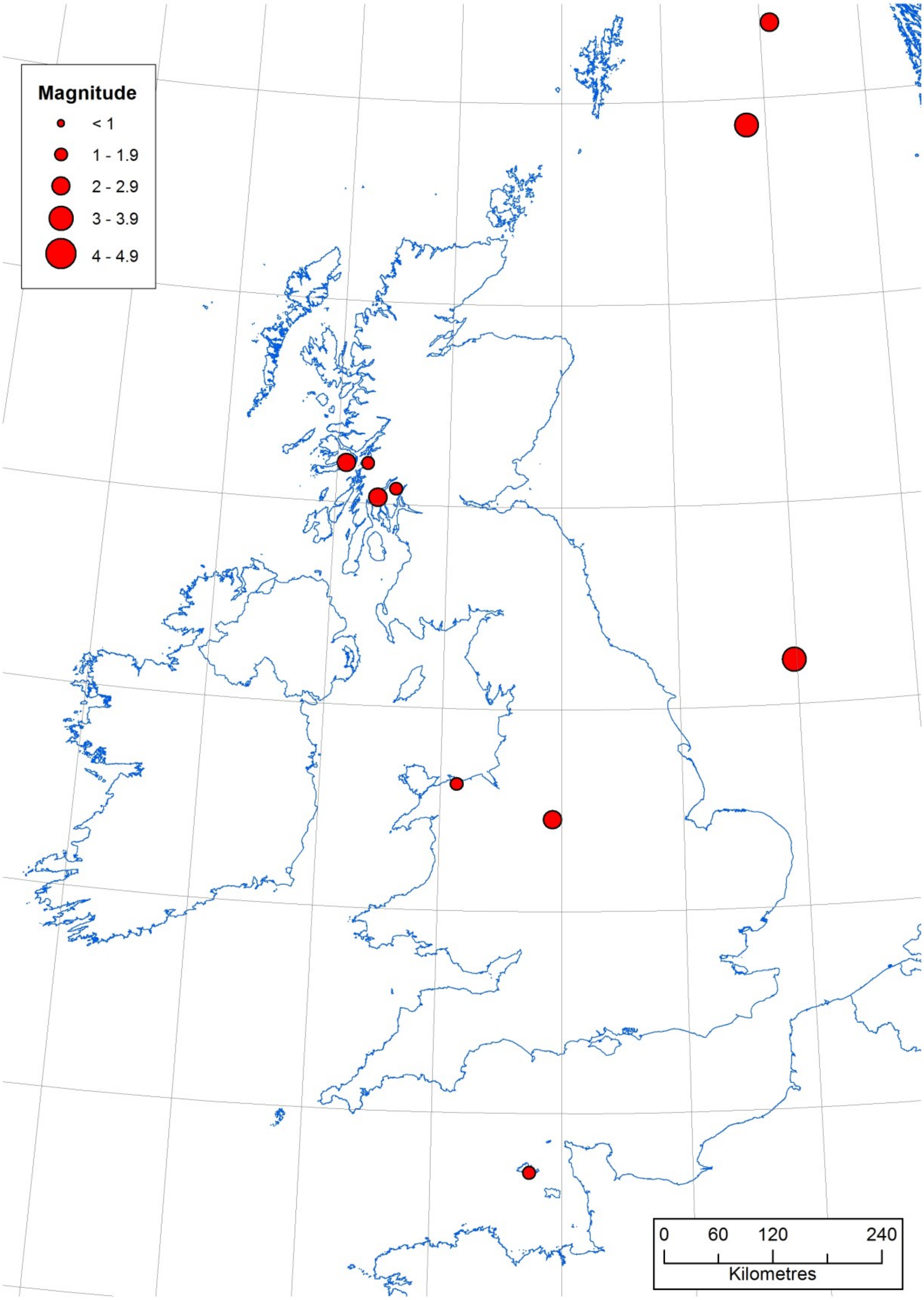
We continue to update the Seismology web pages. These web pages are directly linked to our earthquake database providing near real-time lists of significant earthquake activity, together with automatically generated pages for each event.

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 is contributed. We received 46 replies following the Colwyn Bay, North Wales, earthquake on 13 June 2016 (1.9 ML), 45 replies following a magnitude 2.3 ML earthquake near Liskeard, Cornwall, on 27 October 2016 and 51 replies following a magnitude 2.4 ML earthquake near Lephinmore, Argyll on 24 January 2017.

Data from the questionnaires are grouped by location into 5x5 km squares and an intensity value is assigned to each square, given that at least five responses are received from any square. Where fewer responses are received the intensity is either given as “felt” or “not felt” (which are defined as intensity 1 and 0, respectively).



(a) Macroseismic intensity data for the Lephinmore earthquake on 24 January 2017. Epicentre denoted by yellow star. (b) Number of responses from each grid square.



Events in the reporting period (1 April 2016 – 31 March 2017) for which alerts have been issued. Circles are scaled by magnitude. Five of the alerts are outside the map extent.

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.

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. These document the parameters of these events and provide information on the tectonic setting and background seismic activity in the region.

The seismology web site continues to be widely accessed, with over 62,988 visitors logged in the year (over 41.5 million hits).

We actively use Twitter, Facebook, Audioboo and YouTube to post earthquake alerts, provide news of new web pages, and showcase podcasts and videos of our seismologists. Facebook also offers a way for the public to engage with us by asking questions related to various postings.

The UK School Seismology Project (UKSSP) continues to grow and create new partnerships. The aim of the project is to develop specific resources for teaching and learning seismology in UK schools, including an inexpensive seismometer that is robust enough to be used in schools but still sensitive enough to record earthquakes from the other side of the world. These provide teachers and students with the excitement of being able to record their own scientific data and help students conduct investigations using their own data.

The BGS Earthquake Seismology team participated in an event called 'Power of Our Planet' at Our Dynamic Earth in Edinburgh in October 2016. This provided an opportunity for members of the public to meet a range of BGS scientists and explore a spectacular selection of Earth Science demonstrations and hands-on activities. The aim was to provide an understanding of the ways in which we rely on our planet to preserve our way of life, and the ways in which it can be threatened.

Football-Quakes is an outreach project that aimed to detect seismic disturbances during football matches at the Leicester City Football stadium. The project is a collaboration with Leicester University, SEIS-UK, and a city centre primary school, and resulted in a huge amount of publicity, both nationally and internationally. Leicester University put the project forward as an exemplar of marketing and communications and it came first runner-up in the Guardian University awards 2017.

The MarsQuake education project is a UK Space Agency-funded initiative led by the British Geological Survey with partners from the National Space Academy, University of Leicester and University of Bristol. The project will develop a set of classroom activities and learning resources to support the mission.

The project will be part of the NASA INSIGHT Mission to Mars, and although the launch has been delayed from 2016 to 2018, the UK School Seismology team completed their UKSPACE agency funded project to develop the teaching resources for this project in January 2017. The resources include a booklet[1] and a set of classroom activities. Three thousand hard copies of the booklet have been printed ready to be distributed to teachers alongside the mission launch in 2018.

As part of the MarsQuake project, the UK school seismology team has also developed a new ultra-low cost seismic recording system based on a ‘build your own seismic sensor’ design (constructed from Lego) and a new low cost digitiser designed to work with the Raspberry Pi single board computer system.

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 2016-2017, at least 767 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 BGS Lego seismometer when fully assembled. The seismometer is made only from Lego and a metal spring. The mass on the sensor will stay still (due to its inertia) when the ground moves, this relative motion can then be converted to a voltage with a coil and a magnet.

[1] http://www.bgs.ac.uk/discoveringGeology/hazards/earthquakes/marsquake/home.html

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.

The UK Alliance for Disaster Research (UKADR) was launched in June 2016. BGS is one of the core partners and a founding member. The aim of UKADR is to bring together disaster researchers from all disciplines in the UK in order to aid representation of the research community at government level and to help facilitate the implementation of the Sendai Framework for Disaster Risk Reduction. The Alliance is independent and managed by voluntary contributions from the UK research community.

There is growing recognition of the role that science and scientists can play in reducing disaster risk and building resilience to geohazards, especially when working with people from other research disciplines and various stakeholders, including communities at risk. This often needs new ways of working, potentially in complex settings and difficult environments, to achieve positive and sustainable change.

Susanne Sargeant is continuing to work with researchers from a number of UK universities (including Cambridge, Oxford and Durham among others) and the Overseas Development Institute as a co-investigator on the Earthquakes without Frontiers (EwF) project. EwF is a transdisciplinary research project that aims to increase resilience to earthquakes and landslides in the Alpine-Himalayan Belt, focussing on Kazakhstan, Nepal and Bihar in northern India, and NE China. EwF is entering its final year and the collaboration between the BGS and the Institute of Seismology in Kazakhstan is continuing. Our activities focus on attenuation, magnitude determination and seismic hazard assessment.

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.

Margarita Segou continues to work with researchers from leading EU and UK institutes in an effort to develop a protocol for sharing scientific information and expert advice in the aftermath of natural disasters. The research is part of the ARISTOTLE project, an All Risk Integrated System TOwards Trans-boundary hoListic Early-warning.

BGS are working with the Istituto Nationale Geofisica e Vulcanologia (INGV), Italy, to help better understand deadly earthquake sequences such as the Central Italy sequence of 2016/2017. This has involved the deployment of temporary stations to collect essential data as well as collaboration on the underlying science of such sequences. An aligned project with researchers at the University of Edinburgh, funded by a NERC Urgency Grant, aims to develop testable forecast models for informed decision-making and the creation of a scientific protocol for stress-based modelling applicable to global seismicity.

Margarita Segou is a co-PI on the NERC funded research project REAR (Research Emergency Aftershock Response). The project brings together scientists and Arts-and-Humanities professionals to deliver protocols for the development, communication and dissemination of aftershock forecasts. Collaborating Institutes are University of Edinburgh University of Leeds and the Dublin Institute for Advanced Studies.

Margarita has also received a RCUK-DPRI Kyoto Research Grant to investigate earthquake triggering during the 2016 Kumamoto sequence. Funding supports a long-term visit in the Disaster Prevention Research Institute in Kyoto (Japan) for investigation of aftershock occurrence in Kumamoto region in Kyushu island.

Margarita is also a principal investigator of a proposal to form an international collaboration with UK (BGS, University of Edinburgh, Bristol), USA (University of Stanford, US Geological Survey, Lamont-Doherty Observatory Columbia University) and European (INGV, EPOS) institutes that will explore the processes driving the destructive earthquake sequence that struck the Central Apennines of Italy in 2016.

Ilaria Mosca continues to work within the EwF partnership to develop ground motion and seismic hazard models that can be used by stakeholders engaged in policy making and community-based risk reduction activities. Ilaria has also been working with the Kazakh Institute of Seismology providing support for the development of new national seismic hazard maps.

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 452 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

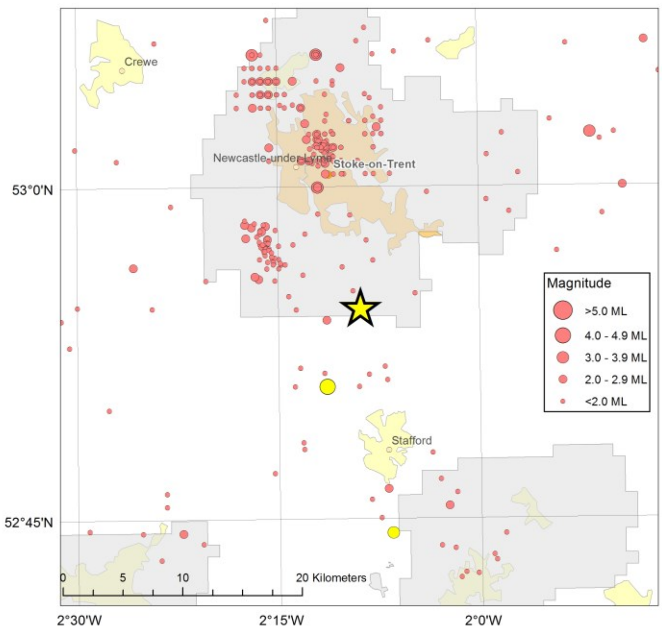
The details of all earthquakes, felt explosions and sonic booms detected by the BGS seismic network have been published in monthly bulletins and compiled in the BGS Annual Bulletins.

There were 214 local earthquakes located by the monitoring network during 2016-2017, with 20 having magnitudes of 2.0 ML or greater, and five having magnitudes of 3.0 ML or greater. All of the latter occurred offshore. Four events with a magnitude of 2.0 ML or greater were reported felt, together with a further 16 smaller ones, bringing the total to 20 felt earthquakes in 2016-2017.

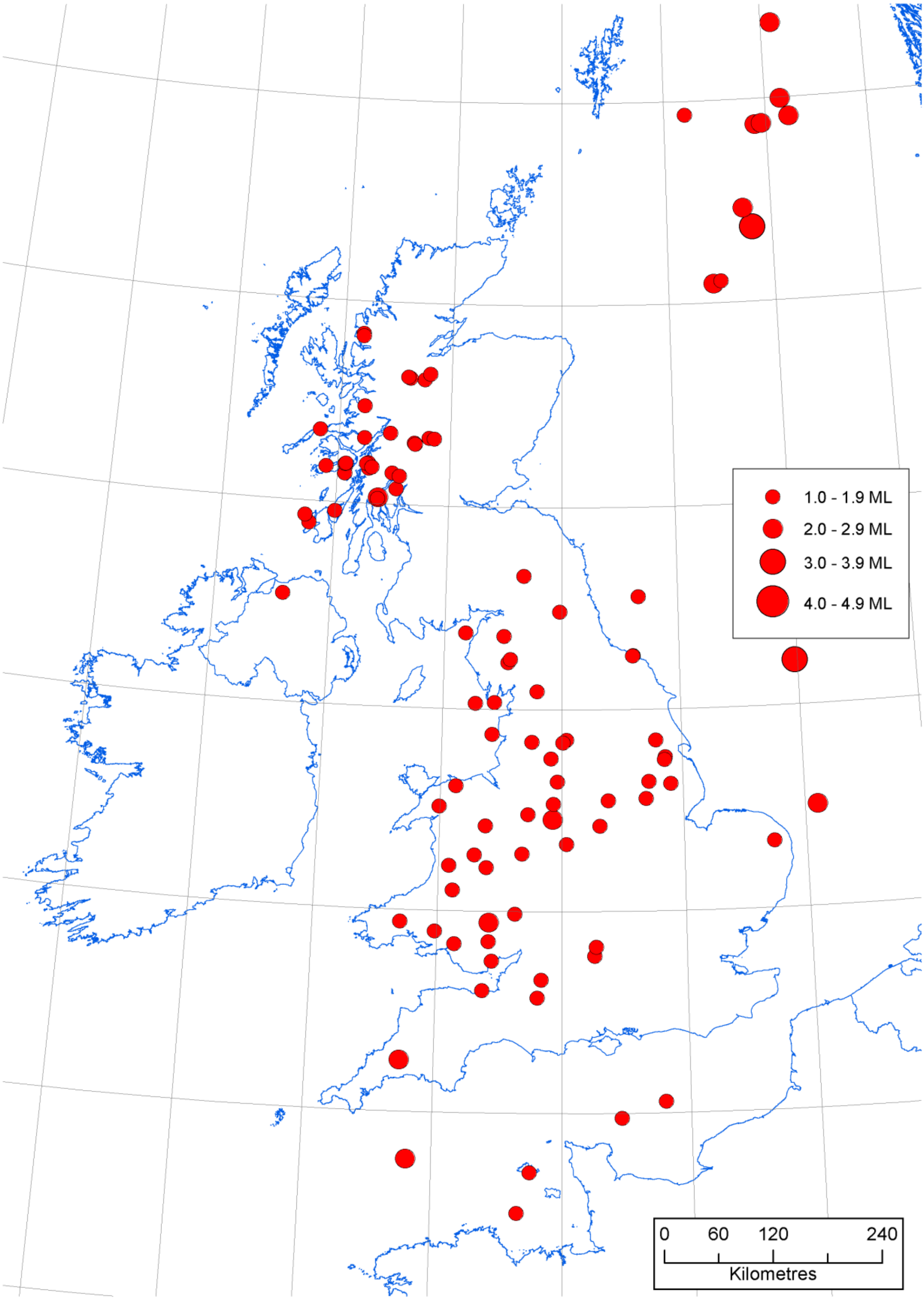
The largest felt earthquake was a magnitude 3.8 ML event on 3 January 2017. The epicentre was in the North Sea about 150 km east of Scarborough. It was only weakly felt in Scarborough.

The largest earthquake on mainland Britain during 2016-2017 was a magnitude 2.6 ML event near Stone, Staffordshire that occurred on 3 March 2017 at 09:28 UTC. The earthquake was only weakly felt by a few people near the epicentre, with a maximum intensity of 2 EMS.

A magnitude 2.3 ML earthquake on 27 October 2016 at 02:08 UTC was widely felt in Cornwall, with a maximum intensity of 3 EMS. The epicentre was on Bodmin Moor about 10 km east of Bodmin and 5 km northwest of Liskeard.



The yellow star shows the epicentre of the Stone earthquake. Red circles show instrumentally recorded earthquakes (1970-2015). Symbols are scaled by magnitude. Grey shaded areas show the Mining Reporting Areas (Coal Authority data). Many of the earthquake around Stoke have been identified as mining-induced during analysis.



Epicentres of all earthquakes in and around the UK detected in the reporting period
(1 April 2016 – 31 March 2017).

Overview of global earthquake activity

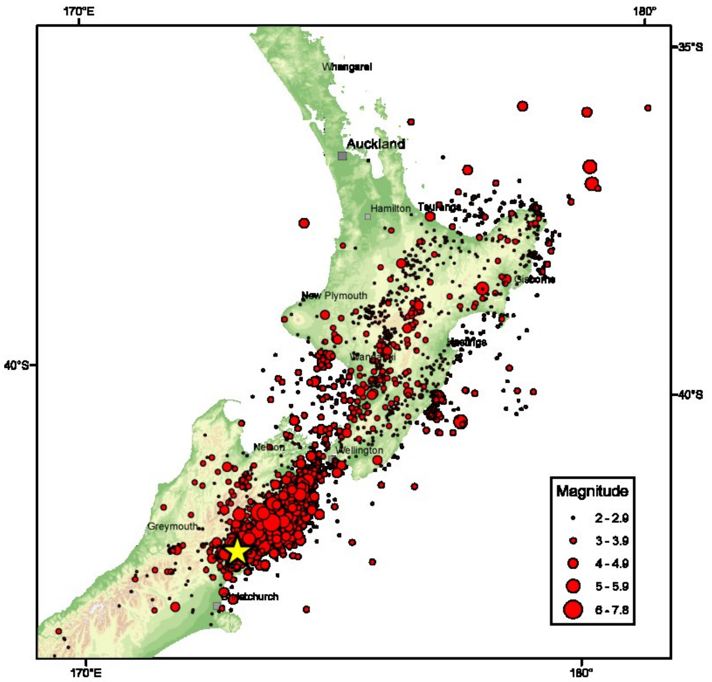
Worldwide, there were 15 earthquakes with magnitudes of 7.0 or greater and 137 with magnitudes of 6.0 or greater. These numbers are in keeping with longer term annual averages based on data since 1900, which suggest that on average there are 16 earthquakes with magnitude 7.0 or greater and 150 with magnitudes of 6.0 or greater each year. Deadly and destructive earthquakes included a magnitude 7 event on Kyushu in southwest Japan and a destructive sequence of earthquakes in Central Italy.

A magnitude 7.0 earthquake occurred on Kyushu, Japan on 15 April 2016. The epicentre was several hundred kilometres northwest of the Ryukyu Trench, where the Philippines plate is subducted beneath Japan and the Eurasia plate. The shallow depth and faulting mechanism of this earthquake suggest that it occurred on a crustal fault within the Eurasia plate.

Earthquakes at this depth are relatively unusual in this part of Japan, since most seismicity in the Kyushu region is related to the subduction of the Philippine plate and occurs at greater depths below the island. Just 13 M 5+ earthquakes have occurred at shallow depths (< 50 km) within 100 km of the April 2016 events over the preceding century. A shallow M 6.6 earthquake in March 2005, just off the north coast of Kyushu and 110 km north of the April 2016 event, caused over 1000 injuries and at least one fatality.

The April 15 earthquake occurred one day after a series of foreshocks in the same region, which included magnitude 6.2 and 6.0 earthquakes.

A magnitude 7.8 earthquake struck the South Island of New Zealand on 14 November 2016. The epicentre was 60 kilometres south-west of the town of Kaikoura.



The yellow star shows the epicentre of the mainshock on 14 November. Red circles, scaled by magnitude, show locations or all subsequent seismicity in New Zealand until the end of November 2016

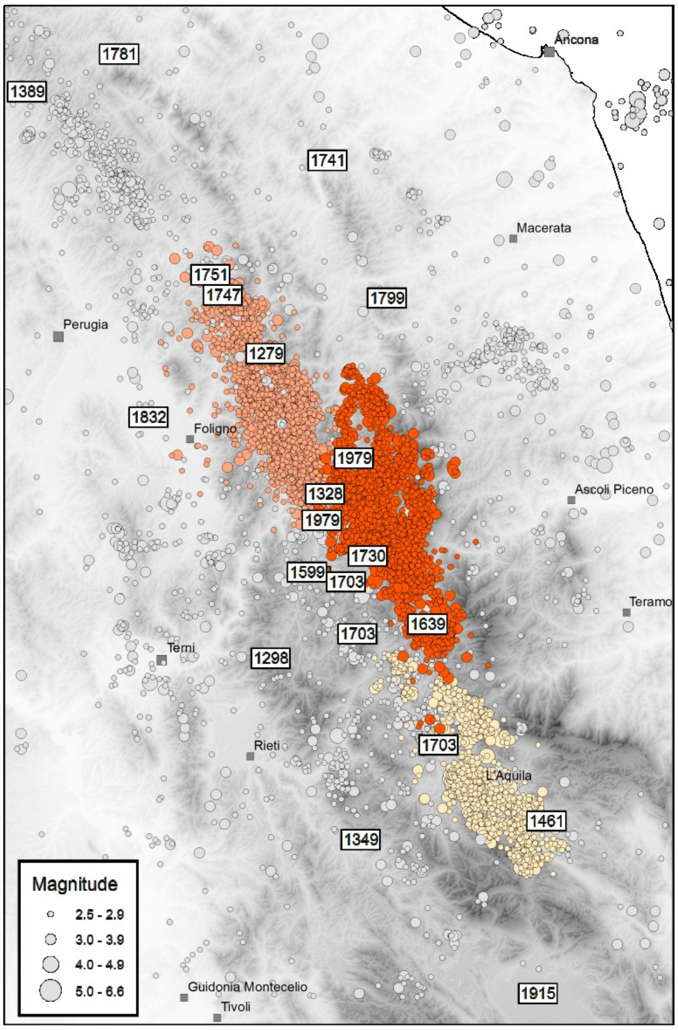
Two people died in the earthquake. Kaikoura was cut off due to landslides, damaged bridges and infrastructure, road subsidence, and the risk of falling debris. Many other major roads in the South Island were also closed because of landslides and damage to bridges. There was also widespread damage to buildings in the city of Wellington.

A complex rupture propagated north for over 200 km continuing offshore and resulting in a localised tsunami of up to 7 m. The largest surface displacements were near the northern termination of the earthquake rupture, at the northeast tip of the South Island. This may explain why aftershocks were concentrated in the north, and why areas north of the rupture, such as Wellington, experienced more damage than areas to the south.

A magnitude 6 earthquake occurred in Central Italy on 24 August, close to the towns of Accumoli and Amatrice. Despite the moderate magnitude, the shallow hypocentre resulted in severe ground shaking and significant damage to the many vulnerable buildings in the region, leading to 299 deaths. The village of Amatrice was devastated.

Two months later, on 26 October, a magnitude 5.9 event occurred on a fault segment 25 km to the north, near the town of Visso. A further four days later, on 30 October, a magnitude 6.5 earthquake, the largest of the sequence, struck the area in between the two previous events, destroying the town of Norcia and surrounding towns. This was the largest earthquake to strike Italy since the 1980 magnitude 6.9 Irpinia earthquake. Fortunately, this event did not result in further casualties, mainly because local residents had already abandoned the previously damaged buildings.

All three events resulted from normal faulting along a 60 km fault zone zone that has been active in both historical and modern times (Chiaraluce *et al*., 2017. This zone lies immediately north of the fault zone that ruptured during the 2009 L'Aquila earthquake sequence and overlaps with the southern end of the 1997 Colfiorito seismic sequence. The loss of life and the damage to buildings underline the pressing need to understand the complexity of the underlying physics of earthquake sequences, and to use this knowledge to anticipate the evolution of such sequences in the future.



Historical seismicity in the Central Italy showing the 2016/2017 Amatrice sequence (red circles); the 1997/1998 Colfiorito sequence; and the 2009 L'Aquila sequence. Other notable historical earthquakes are marked by the dates in rectangles.

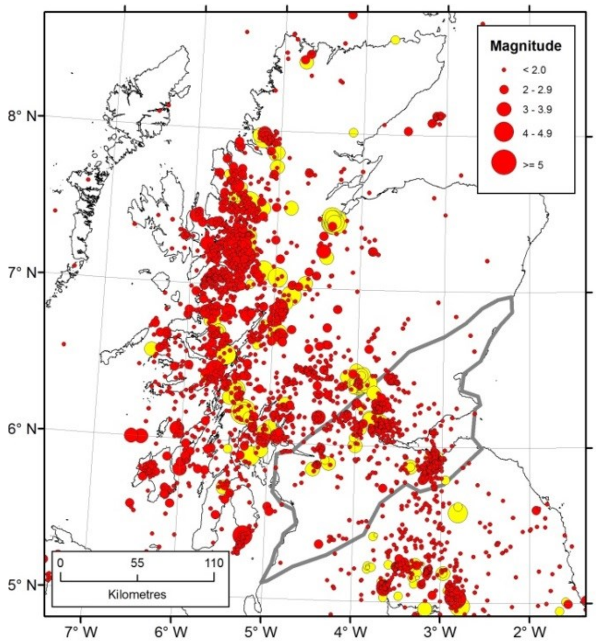
Research

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

A study to improve understanding of the levels of induced seismic activity that could be associated with unconventional oil and gas activities in Scotland was commissioned by the Scottish Government (Baptie *et al*., 2016). This also examined regulatory and non-regulatory actions that can be taken to mitigate any noticeable effects on communities.

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

Most earthquake activity in Scotland is north of the Highland Boundary Fault, on the west side of mainland Scotland, and there are fewer earthquakes in northern and eastern Scotland. It is rarely possible to associate these earthquakes with specific faults because of uncertainties both in the earthquake location estimates, which are typically several kilometres, and our limited knowledge of faulting below the surface.



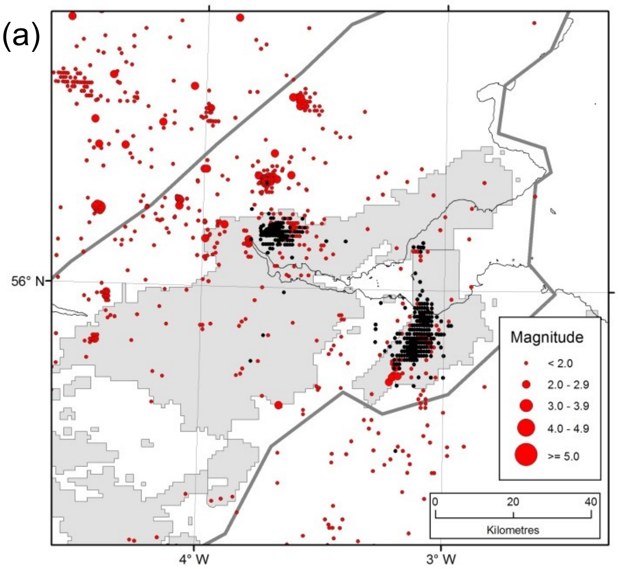
Historical (yellow circles) and instrumentally recorded (red circles) earthquakes from the BGS catalogue for Scotland. Circles are scaled by magnitude.

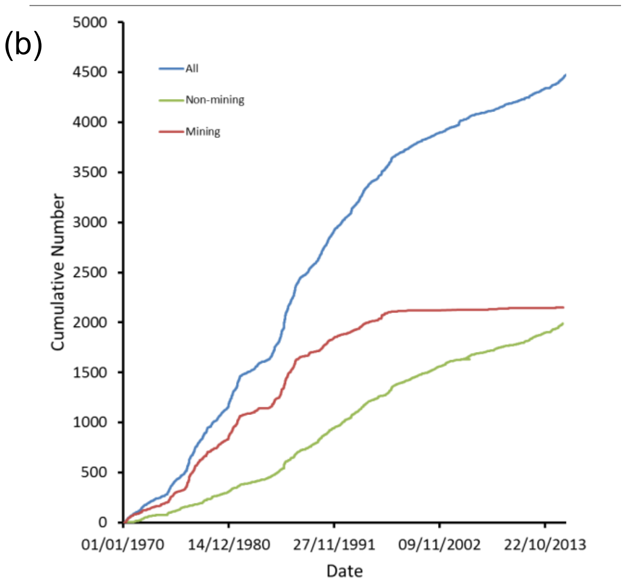
Earthquake activity in the Midland Valley of Scotland is lower than that north of the Highland Boundary Fault, and many of the recorded earthquakes in this area in the 1970s, 1980s and 1990s were induced by coal-mining. Most of these mining induced earthquakes are small (the largest in Scotland had a magnitude of 2.6 ML) and since the decline of the coal-mining industry in the 1990's, very few mining-induced earthquakes have been recorded.

These mining induced events represent a temporary perturbation and they need to be removed from the earthquake catalogue so that an accurate measure of natural earthquake activity rates can be established. We did this by defining a simple spatial filter based on the Mining Reporting Areas, as issued by the Coal Mining Authority. All events from within these areas are removed from the catalogue.

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

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





(a) Red circles show instrumentally recorded earthquakes (1970-2015). Symbols are scaled by magnitude. Grey shaded areas show the Mining Reporting Areas (Coal Authority data). Black circles show earthquakes identified as mining-induced during analysis. (b) Cumulative number of earthquakes as a function of time from 1970 to end of 2015. The blue line shows all recorded earthquakes. The red line shows earthquakes removed by a spatial filter and the green line shows the earthquake data after all events in the Mining Reporting Areas have been removed. Earthquake data from the British Geological Survey UK Earthquake Catalogue © NERC 2016.

Research

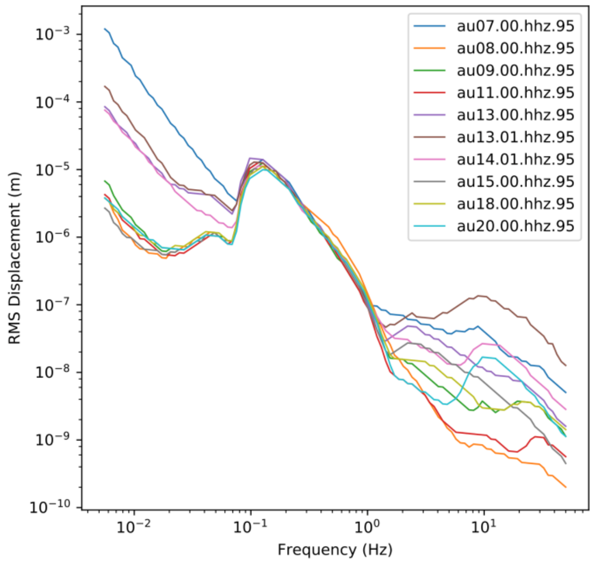
Noise and Detection Capability

Ambient Earth noise is present in all recordings. It affects data quality and can limit the ability to detect and reliably locate small transient signals from earthquakes or other disturbances. We have analysed ambient noise levels at all sites across the UK and used the results to improve models of the detection capability of the network.

Seismograms always contain noise from ambient Earth vibrations as well as transient recordings from earthquakes. Seismic noise from human activity is often referred to as “cultural noise” and originates primarily from the coupling of traffic and machinery energy into the Earth. This cultural noise propagates mainly as high-frequency surface waves (1-100 Hz) that attenuate within a few kilometres of the noise source and often shows very strong diurnal variations. The frequency content is similar to that for small and moderate local earthquakes. As a result, high noise levels can limit the ability to detect and reliably locate small transient signals from earthquakes or other disturbances.

We used power spectral density (PSD), calculated from one hour segments of continuous data, to characterize noise levels in a range of frequencies or periods at all stations in the UK network. A statistical analysis of the PSDs yields probability density functions (PDFs) of the noise power for each of the frequency bands at each station and component. We use the median, 5^{th} and 95^{th} percentiles of the PDF as the basis of median, low and high noise models for each station.

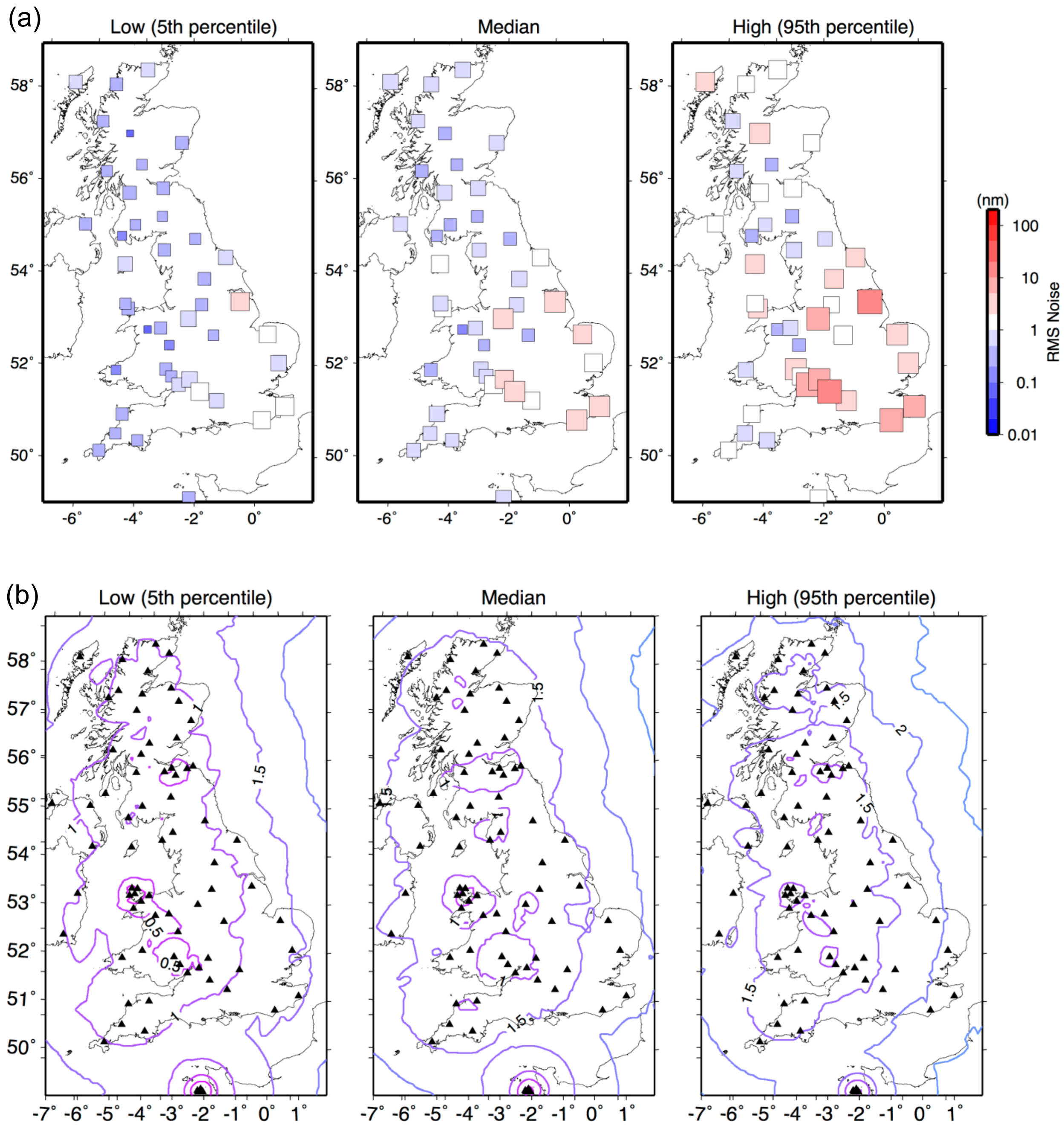
We find that noise can vary significantly even for stations that are close together. For example, the variations in RMS displacement amplitudes at frequencies above 1 Hz between stations in the Vale of Pickering, Yorkshire, can exceed two orders of magnitude. The quietest stations show RMS amplitudes of less than 1 nm, while noisier stations can show RMS amplitudes of almost 100 nm. This is primarily a result of proximity to cultural noise sources.



RMS displacement amplitudes of the 95^{th} percentile of background noise as a function of frequency for stations around the Vale of Pickering in Yorkshire. RMS amplitudes are calculated using a of ground velocity in a constant relative bandwidth of one decade.

Similarly, RMS noise amplitudes for our low, median and high noise models show systematic variation across the UK that generally reflects proximity to noise sources and site geology. Sites on soft rock in the south east of England show high noise levels, whereas sites on hard rock in remote rural locations show low noise levels.

Previous models of the detection capability used constant noise levels at all stations, with 2nm, 4 nm and 20 nm for the low, median and high noise models. We use our results to determine detection capability for a network where noise varies realistically. The results suggest a rather better detection capability in the UK than previously expected.



(a) RMS amplitudes for selected stations. The low, median and high noise values are calculated from RMS displacement amplitudes in one minute windows over one year. A 2 Hz high pass filter was applied to the signals before calculating the amplitudes. (b) Detection capability of the network in low, median and high noise conditions. The contours show earthquake magnitudes that can be detected. Signal amplitudes must exceed the background noise level by a factor of ten at five or more stations.

Research

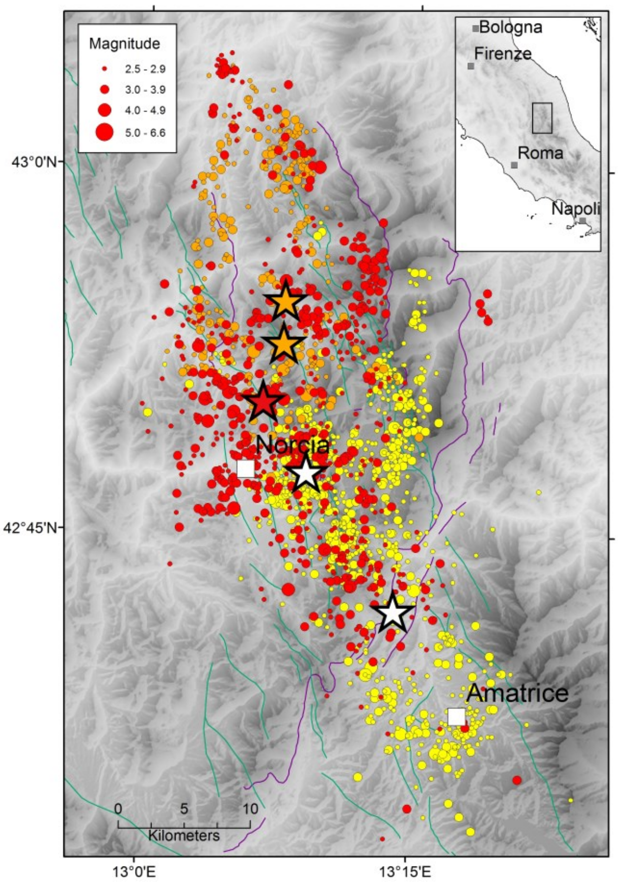
The Amatrice Earthquake Sequence

Following the devastating Amatrice earthquake in the Central Apennines of Italy, BGS secured funding from NERC to deploy 24 earthquake sensors in the affected area to supplement permanent and temporary stations deployed by the Istituto Nationale Geofisica e Vulcanologia (INGV). This provides an unparalleled dataset to analyse how each earthquake within the sequence contributes to the next, and how this behaviour evolves through space and time.

In August 2016, a destructive earthquake sequence, including at least five events with magnitude larger than 5.4 Mw, began to unfold in Central Italy. The events spanned a 50-km fault zone that has been active in both historical and modern times. The loss of life and the damage to buildings underline the pressing need to understand the complexity of the underlying physics of earthquake sequences, and to use this knowledge to anticipate the evolution of such sequences in future.

After the first earthquake in the sequence, on 24 August 2016, BGS, with funding from NERC, deployed 24 sensors to supplement the 28 permanent and 23 temporary stations deployed by Istituto Nationale Geofisica e Vulcanologia (INGV) and the 19 accelerometer stations operated by the Italian Department of Civil Protection. This network has an average station spacing of ~5 km and will provide an unparalleled dataset to analyse how each earthquake within the sequence contributes to the next, and how this behaviour evolves through space and time.

A NERC funded project is focussing on the development of testable forecast models for informed decision-making and the creation of a scientific protocol for stress-

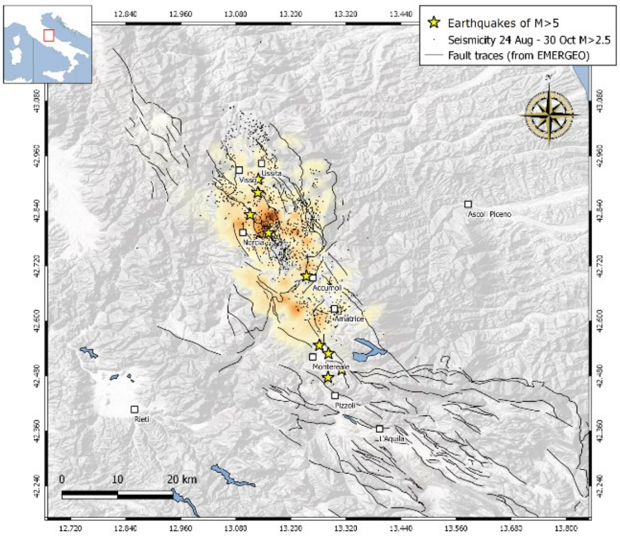


The white stars show the locations M=6 Amatrice earthquake on 24 August along with a magnitude 5 aftershock a few hours later. The orange stars show M=5.4 and M=5.9 events that occurred 32 minutes apart on 26 October. Four days later on 30 October a M=6.5) event struck, devastating the town of Norcia. Yellow circles show events between 24 August and 26 October. Orange circles show events between 26 October and 30 October. Red circles show events after 30 October.

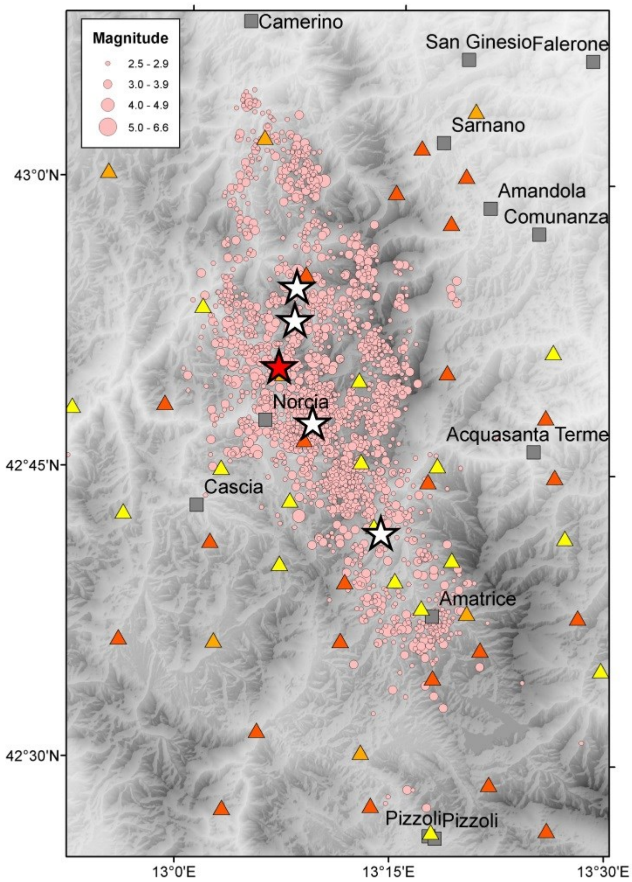
based modelling applicable to global seismicity.

This research has been carried out in collaboration with the University of Edinburgh and INGV-Rome. Recent scientific results were presented in the British Seismological Meeting and in the Annual Meeting of the Seismological Society of America

The development of stress-based models for aftershock forecasting of evolving sequences presents a clear advantage over easier statistical approaches that rely on empirical knowledge but do not improve our understanding of earthquake physics. Instead physics-based approaches, as shown in the figure below, allow us to improve our knowledge on earthquake nucleation and the conditions under which large earthquakes nucleate.



Aftershock Seismicity Forecast in Central Apennines. Shaded colours represent expected number of events in the time period between 24/08 (Amatrice) and 30/10 (Norcia) with magnitude larger than M=2.5. Note the higher aftershock rates expected near Norcia, promoted by the largest aftershock on 24/08 and the 26th October earthquakes near Visso village.



Sensors installed by BGS/NERC (red) along with permanent (orange) and temporary sensors (yellow) installed by INGV.

The unprecedented, for Europe, dataset has been the basis for an international collaboration with UK (BGS, Universities of Edinburgh and Bristol), USA (University of Stanford, US Geological Survey, Lamont-Doherty Observatory of Columbia University) and European (INGV-Rome, EPOS) institutes. The project aims to explore the processes driving this destructive earthquake sequence and quantify how each earthquake in a series contributes to the next, and how this behaviour evolves through space and time

Research

Supporting self-recovery after disasters

'Self-recovery' refers to what most households affected by disasters do to 'repair, build or rebuild their shelter themselves or through local builders' (Schofield and Miranda Morel, 2017). BGS are part of a consortium with CARE International, University College London and the Overseas Development Institute undertaking research to better understand how self-recovery can be better supported by the humanitarian sector, geoscientists and engineers.

Self-recovery (SR) tends to be the predominant route to recovery after disasters and often happens with little or no external assistance (Parrack *et al*., 2014). It is crucial that this process is well-supported by scientific knowledge of geohazards and the environment to help communities build back safer and better and not 'rebuild risk'.

BGS scientists have undertaken community-based fieldwork with humanitarian practitioners, engineers and social scientists to investigate self-recovery from a range of perspectives. So far, we have explored cases of self-recovery in rural communities following rapid-onset disasters in the Philippines (typhoons in 2013 and 2015) and Nepal (the 2015 Gorkha earthquake).

A strong awareness of the environment is common to the communities we visited in both the Philippines and Nepal. In the Philippines, people's understanding of geohazards appears to come primarily from first-hand experience (typhoons occur regularly) and through transfer of ancestral knowledge, with more varying and limited direct input from scientific organisations. There is evidence that individuals' awareness of geohazards and perceptions of event frequency have influenced some rebuilding.

In Nepal, the focus was on rural communities in Dhading District that had been severely affected by the 25 April 2015 Gorkha earthquake. Besides the direct impact of the earthquake and its aftershocks on shelter, many of these communities and the roads leading to them were, and continue to be, affected by landslides. There were also many reports of water supplies being disrupted by the earthquake. This, and ongoing damage to roads, is impeding the recovery process.

Rebuilding efforts focus on seismic resistance but it is clear that these communities are now exposed to a multiple geohazards at places that were previously considered safe. There is very limited scientific input into the self-recovery decision-making process although some information regarding safe siting of houses is given by the government.

The two cases show the impact of the natural environment on SR and the limited extent to which scientific knowledge supports this process. Finding ways for geoscience to better support SR is therefore crucial.

The upper photograph shows an example of ongoing rebuilding at Budhathum VDC (Village Development Committee) in the Dhading District in Nepal, east of the epicentre and approximately 70 km NW of Kathmandu. The lower photograph shows an example of a temporary shelter, at Dharka VDC, also in Nepal.

Research

Correcting Local Magnitude Estimates Discrepancies at Near-Event Distances

A Local Magnitude scale is used throughout the BGS earthquake catalogue. The scale is similar to the original Richter Scale. Recent research has shown that amplitude measurements from epicentral distances of less than 15-20 km considerably overestimate event magnitudes compared to more distant observations. We have revised the existing magnitude scale to correct for this effect.

Recent research has shown that amplitude measurements from epicentral distances of less than 15-20 km considerably overestimate event magnitudes compared to more distant observations (Butcher *et al.*, 2017). Similarly, magnitudes calculated for earthquakes induced by hydraulic fracturing at Preese Hall, Lancashire (Clarke *et al.*, 2014) using ground motions recorded on seismometers at distances of a few kilometres away were unrealistically high.

A detailed examination of the BGS earthquake catalogue shows that individual station magnitudes for stations within 5 km of an earthquake are up to an order of magnitude higher than station magnitudes at other stations (Luckett *et al.*, 2017). In many cases this would cause a considerable increase in the event magnitude, compared to the magnitude expected from macroseismic information. As a result, such amplitudes have not been included when calculating the magnitude.

This issue is demonstrated in the figure opposite, which shows the residuals between station magnitude and event magnitude for 92 earthquakes selected from the BGS catalogue.

The A_0 term in Richter's (1935) local magnitude relationship can be expressed as

$$-\log_{10} A_0 = a \log_{10} r + b\, r + c$$

where r is the hypocentral distance and a, b and c are constants. The a and b terms represent the effect of geometrical spreading and attenuation respectively. Hutton and Boore (1987) find the following is equivalent to the original Richter tables for California.

$$-\log_{10} A_0 = 1.11 \log_{10} r + 0.00189\, r - 2.09$$

These values of the constants are currently used for determination of earthquake magnitude in the UK. Ottemöller and Sargeant (2013) used data recorded on the BGS seismic network to develop an ML scale for the United Kingdom, finding a similar relationship to Hutton and Boore (1987)

$$-\log_{10} A_0 = 1.06 \log_{10} r + 0.00121\, r - 1.98$$

Butcher *et al.* (2017) suggest that the magnitude discrepancy is a result of higher attenuation in near-surface geology, and requires a change in the attenuation term of the ML scale. They use data collected at distances of less than 10 km from a sequence of mining events near New

Ollerton, Nottinghamshire, to determine new constants for the ML scale, finding the following values

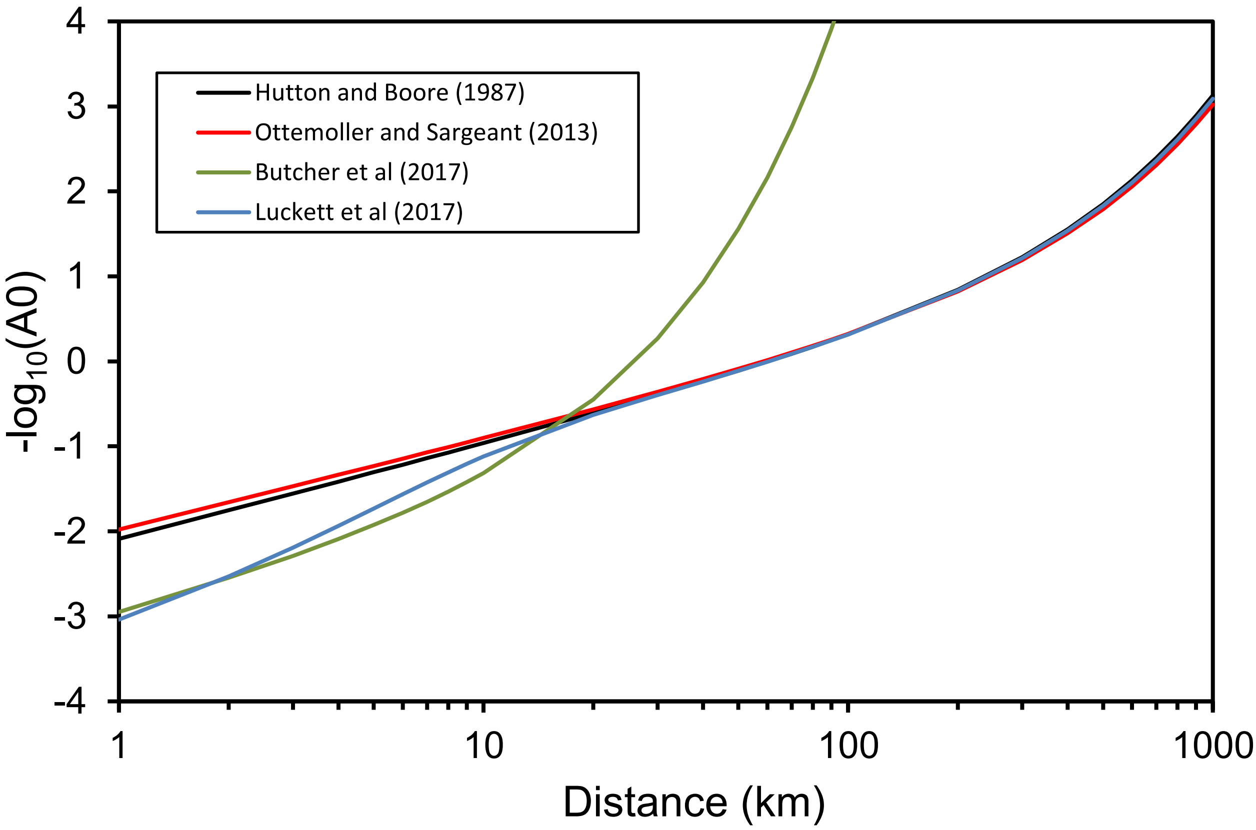
$$-\log_{10} A_0 = 1.17 \log_{10} r + 0.0514\, r - 3.0$$

Butcher *et al.* (2017) suggest that the increase in the attenuation term 0.00189 to 0.0514 is representative of a raypath within a slower, more attenuating sedimentary layer compared to the continental crust and that this magnitude scale should be used when local monitoring networks are within 5km of the event epicentres. Strictly, this scale is only valid for data from the New Ollerton sequence, however, Butcher *et al*. (2017) show that it gives reasonable results when applied to the earthquakes induced by hydraulic fracturing at Preese Hall. Additionally, the scale cannot be used above the suggested cut-off distance of 5 km as it will result in incorrect estimates of magnitude. This cut-off distance is not well constrained.

Luckett *et al.* (*2017*) suggest that the higher than predicated amplitudes at distances of less than 10-20 km are a result of high amplitude surface waves. These are an important part of the waveform for shallow sources at distances of less than 20 km, but attenuate quickly with distance. They suggest adding an extra exponential term to account for this effect, and determine the following expression for a UK data set.

$$-\log_{10} A_0 = 1.11 \log_{10} r + 0.00185\, r - 1.16e^{-0.2r} - 2.09$$

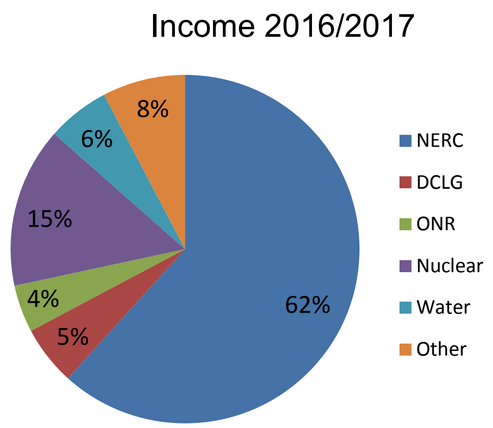
This expression results in a significant reduction in residuals when compared to the Hutton and Boore (1987) relationship. Luckett *et al*. (*2017*) also apply this relationship to data from Preese Hall and New Ollerton and find that the results are in good agreement with those of Clark *et al*. (2014) and Butcher *et al*. (2017).

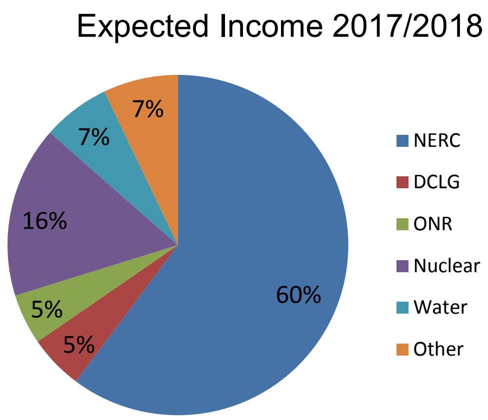


A_0 correction terms derived by Hutton and Boore (1987), Ottemöller and Sargeant (2013), Butcher *et al*. (2017) and Luckett *et al*. (2017).

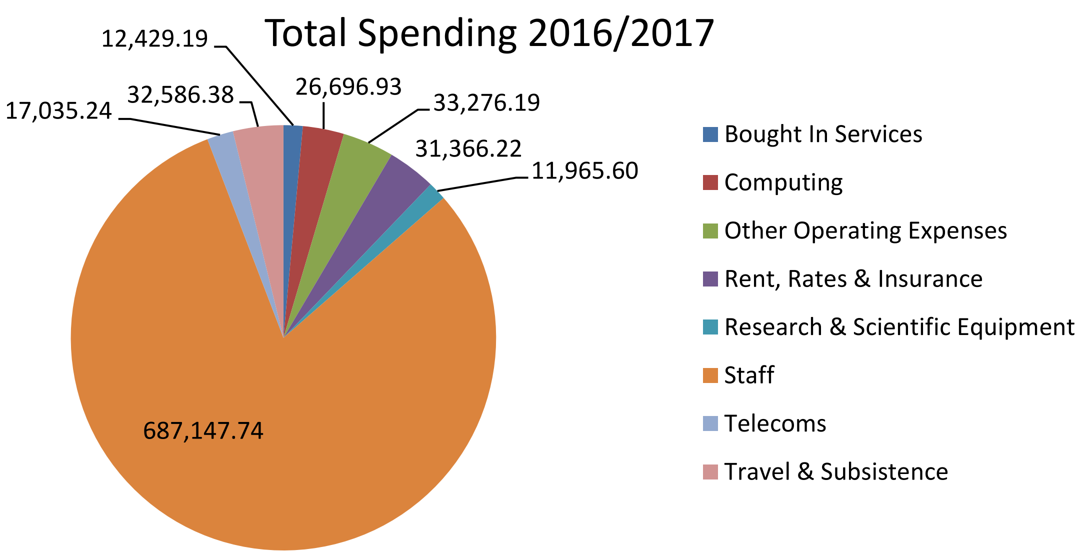
Funding and Expenditure

In 2016-2017 the project received a total of £846K, including a contribution of £522k from NERC. Some of this was won from specific funding calls. This was matched by a total contribution of £324k from the customer group drawn from industry, regulatory bodies and central and local government. This is a slight increase on the previous year.





The projected income for 2017-2018 is slightly less than that received in 2016-2017, mainly as a result in the reduction of direct NERC funding. This reflects a reduction in NERC funding for BGS in general. The NERC contribution for 2017-2018 currently stands at £465k, but we hope to increase this through applications for additional funding through the year. The total expected customer group contribution currently stands at £308k. Currently, other potential sponsors are being explored.



Total spending in 2016/2017 was approximately £852k, 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. Thanks also to Alice Walker who proof read the final version and made many helpful suggestions. 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
Rob Clark	Field engineer, installation, operation and repair of seismic monitoring equipment
Heiko Buxel	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
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., 2017. Operational Seismic Monitoring During Hydraulic Fracturing. British Geological Survey Open Report, OR/17/034.

Baptie, B. and Horleston, A., 2017. Baseline Seismic Monitoring. British Geological Survey Open Report, OR/17/035

Baptie B., Segou M., Ellen R. and Monaghan, A., 2016. Unconventional Oil and Gas Development: Understanding and Monitoring Induced Seismic Activity. British Geological Survey Open Report, OR/16/042, 92pp.

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Appendix 3: Publication Summaries

Operational Seismic Monitoring During Hydraulic Fracturing.

Baptie, B., 2017.

This report was produced by the British Geological Survey (BGS) at the request of the Oil and Gas Authority (OGA) to provide an overview of the requirements for local seismic monitoring required for unconventional oil and gas activities in UK in order to comply with existing regulations.

Baseline Seismic Monitoring.

Baptie, B. and Horleston, A., 2017.

In this report we discuss some of the guiding principles for baseline seismic monitoring using a network of seismic sensors. These include; the design and installation of a network of sensors to ensure reliable detection and location of seismic activity in the area of interest; duration of monitoring and its dependence on background earthquake activity rates.

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

Baptie B., Segou M., Ellen R. and Monaghan, A., 2016.

Scotland is characterised by low levels of earthquake activity and the risk of damaging earthquakes is low. The largest recorded earthquake in Scotland had a magnitude of 5.2 ML with only two other earthquakes of 5 ML or greater in the last 400 years. Most earthquake activity in Scotland is north of the Highland Boundary Fault, on the west side of mainland Scotland, with less activity in northern and eastern Scotland. Earthquake activity in the Midland Valley of Scotland is also lower and in the 1970's to 1990's was mostly induced by coal-mining. On average there are eight earthquakes with a magnitude of 2 ML or above in Scotland every year.

Catalogues of earthquake activity in Scotland are incomplete at magnitudes below 2 ML and for higher magnitudes prior to 1970. This is due to the detection capability of the seismometer networks. This limits identification of areas that might present an elevated seismic hazard for Unconventional Oil and Gas (UOG) operations. Limited information on the stress in the Earth's Crust mean that it is not possible to identify areas where faults are more likely to be reactivated.

Hydraulic fracturing to recover hydrocarbons is generally accompanied by earthquakes with magnitudes of less than 2 ML that are too small to be felt. In the United States, the large number of hydraulic fracturing operations (1.8 million) and the small number of felt earthquakes directly linked to them (3) suggests that the probability of induced earthquakes that can be felt is small. In western Canada, the increase in earthquakes over the last ten years corresponds to the increase in hydraulic fracturing, suggesting an increase in induced earthquakes. There have also been a number of induced earthquakes with magnitudes larger than 3 in Canada, including a magnitude 4.4, which is the largest earthquake linked to hydraulic fracturing in the world. However, as in the US, the probability of induced earthquakes that can be felt appears small given the large number of hydraulically fractured wells (>12,000).

In the UK, regulatory measures for the mitigation of induced seismicity (DECC, 2013) include: avoiding faults during hydraulic fracturing; assessing baseline earthquake activity; monitoring seismic activity during and after fracturing; and a 'traffic light' system to control injection. These are similar to regulatory measures that are in place in the US and Canada. In the UK, the magnitude limit for hydraulic fracturing operations (0.5 ML) is considerably lower than California (2.7 ML) and Illinois, Alberta and British Columbia (4.0 ML) and improved monitoring of seismicity will be required to implement the UK limit.

British Standards define limits for ground vibrations caused by blasting and quarrying above which cosmetic damage could take place. Modelling of ground motions for a range of earthquake magnitudes suggests that those with magnitudes of 3 or less are unlikely to exceed the limits for cosmetic damage except at distances less than a few kilometres.

Improved understanding of the hazard from induced earthquakes and the successful implementation of mitigation measures requires additional data from a number of sources:

(1) Improved monitoring and higher quality earthquake catalogues. Data should be openly available to maintain public confidence.

(2) Geological and geophysical data to map sub-surface faults in high resolution, measurements of the stress field and hydrological properties of the sub-surface.

(3) Industrial data from hydraulic fracturing operations.

Unconventional Gas Exploration and Extraction: Baseline Characterisation of Seismicity

Baptie,B., Jordan, C., Mosca, I., Cigna, F., Burke, S., McCloskey, J., Nic Bhloscaidh, M., Bean, C. and Möllhoff, M., 2016.

This assessment of the potential risk of seismic activity induced by UGEE operations has examined international experience of such induced activity, natural seismic activity in the island of Ireland, methodologies for monitoring distortion of the surface and of background and induced seismic activity, and developed techniques for predicting induced seismicity. There is general consensus that UGEE operations can result in low magnitude seismic activity from the hydraulic fracturing process but that these events are unlikely to cause damage or even be felt. Larger events could occur if slip on existing faults is initiated, but again this is considered to be high unlikely in Ireland where the available data indicates the rate of natural seismicity to be extremely low. A greater risk is perceived through injection of high volumes of wastewater that might result from UGEE operations and so any such proposals should be examined in detail in the context of the local site geology. Modelling techniques developed by this project offer potential to predict earthquake activity, including fracture lengths, but better baseline data on the geological structure of the study areas and background seismicity is required to provide input parameters for the models. Using conservative assumptions, the modelling demonstrated that fracture lengths from hydraulic fracturing are relatively short and extremely unlikely to exceed 500m; as a consequence, pollution of aquifers would not occur by movement of pollutants along fracture paths as long as the separation between the fracture zone and the aquifer exceeds this distance. Detailed seismic monitoring would be required during any UGEE operations and linked to a traffic light system implemented to control operations should seismic activity occur.

Local magnitude discrepancies for near-event receivers: implications for the U.K. Traffic-Light Scheme.

Butcher, A., Luckett, R., Verdon, J.P., Kendall, J.-M., Baptie, B. and Wookey, J., 2017.

Local seismic magnitudes provide a practical and efficient scale for the implementation of regulation designed to manage the risk of induced seismicity, such as Traffic-Light Schemes (TLS). We demonstrate that significant magnitude discrepancies (up to a unit higher) occur between seismic events recorded on nearby stations (<5 km) compared with those at greater distances. This is due to the influence of sedimentary layers, which are generally lower in velocity and more attenuating than the underlying crystalline basement rocks, and requires a change in the attenuation term of the ML scale. This has a significant impact on the United Kingdom's (U.K.) hydraulic fracturing TLS, whose red light is set at ML 0.5. Because the nominal detectability of the U.K. network is ML 2, this scheme will require the deployment of monitoring stations in close proximity to well sites. Using data collected from mining events near New Ollerton, Nottinghamshire, we illustrate the effects that proximity has on travel path velocities and attenuation, then perform a damped least-squares inversion to determine appropriate constants within the ML scale. We show that the attenuation term needs to increase from 0.00183 to 0.0514 and demonstrate that this higher value is representative of a ray path within a slower more attenuating sedimentary layer compared with the continental crust. We therefore recommend that the magnitude scale $ML=\log(A)+1.17\log(r)+0.0514r-3.0$ should be used when local monitoring networks are within 5 km of the event epicenters.

The problem with magnitudes calculated using nearby stations

Luckett, R. and Butcher, A., 2016.

In April 2011, fracking near Blackpool caused a 2.4 ML earthquake at a shallow depth. This was felt by local people and there was considerable public concern. The British Geological Survey (BGS) installed temporary seismic stations close to the epicentre and recorded several subsequent, smaller events. There was, however, some ambiguity over the magnitude of these later events. The magnitudes calculated for the temporary stations were too high for unfelt events that were not, in general, recorded on the national network. A single induced earthquake was recorded both by the temporary stations and by a few stations of the UK national network. The local magnitude calculated from amplitudes recorded on the more distant stations was1.2 ML but the very nearby stations recorded amplitudes corresponding to a magnitude of 2.3 ML. In subsequent studies, this one event was used to scale amplitudes from the nearby stations to magnitudes that were probably similar to the magnitudes that would have been calculated using distant stations – a most unsatisfactory solution. The regulatory approach adopted in the UK to manage the risk of induced seismicity is a 'traffic light' monitoring scheme, with a remedial action level, or 'red light', set at 0.5 ML. As the UK national network has at a nominal detection level of ML > 2, the installation of local seismic stations is critical for the operation of this scheme. However, the suitability of the current UK local magnitude scale is questionable, given that it was not calibrated using very near-receiver events. In fact, the evidence of magnitude discrepancies demonstrated near Blackpool and elsewhere suggests that the scale is not suitable. The single event recorded on both nearby and distant stations at Blackpool is not sufficient to base any further work on. However, analysis of the BGS catalogue shows that this affect has been observed on several other occasions. In particular, over 500 small earthquakes were recorded by a network installed within a few kilometres of the New Ollerton coal mine in 2014. Those events that were also recorded by stations of the UK national network had magnitudes calculated using the local network much larger than those calculated at more distant stations. We use this data to analyse amplitudes recorded very close to earthquakes and test various ideas. We then discuss possible alternatives to the current UK ML scale that might allow near event seismic data to be used to calculate robust magnitudes.

SISMIKO: emergency network deployment and data sharing for the 2016 central Italy seismic sequence

Moretti, M. *et al.*, 2016.

At 01:36 UTC (03:36 local time) on August 24th 2016, an earthquake Mw 6.0 struck an extensive sector of the central Apennines (coordinates: latitude 42.70° N, longitude 13.23° E, 8.0 km depth). The earthquake caused about 300 casualties and severe damage to the historical buildings and economic activity in an area located near the borders of the Umbria, Lazio, Abruzzo and Marche regions. The Istituto Nazionale di Geof- isica e Vulcanologia (INGV) located in few minutes the hypocenter near Accumoli, a small town in the province of Rieti. In the hours after the quake, dozens of events were recorded by the National Seismic Network (Rete Sismica Nazionale, RSN) of the INGV, many of which had a ML > 3.0. The density and coverage of the RSN in the epicentral area meant the epicenter and magnitude of the main event and subse- quent shocks that followed it in the early hours of the seismic sequence were well constrained. However, in order to better constrain the localizations of the aftershock hypocenters, especially the depths, a denser seis- mic monitoring network was needed.

Just after the mainshock, SISMIKO, the coordinating body of the emergency seismic network at INGV, was activated in order to install a temporary seismic network integrated with the existing permanent network in the epicentral area. From August the 24th to the 30th, SISMIKO deployed eighteen seismic stations, generally six components (equipped with both velocimeter and accelerometer), with thirteen of the seismic station transmitting in real-time to the INGV seismic monitoring room in Rome. The design and geometry of the temporary network was decided in consolation with other groups who were deploying seismic stations in the region, namely EMERSITO (a group studying site-effects), and the emergency Italian strong motion network (RAN) managed by the National Civil Protection Department (DPC). Further 25 BB temporary seismic stations were deployed by colleagues of the British Geological Survey (BGS) and the School of Geo- sciences, University of Edinburgh in collaboration with INGV.

All data acquired from SISMIKO stations, are quickly available at the European Integrated Data Archive (EIDA). The data acquired by the SISMIKO stations were included in the preliminary analysis that was performed by the Bollettino Sismico Italiano (BSI), the Centro Nazionale Terremoti (CNT) staff working in Ancona, and the INGV-MI, described below.

Seismic hazard assessment for Pavúa, Mozambique. – Commercial - in - Confidence

Mosca, I., Ellen, R. and Sargeant, S., 2016.

This report presents a probabilistic seismic hazard assessment (PSHA) for Pavúa Hydropower Project. This was completed as a desk study without any fieldwork.

Earthquake science in DRR policy and practice in Nepal.

Oven, K., Milledge, D., Densmore, A., Jones, H., Sargeant, S. and Datta, A., 2016.

Nepal is a geologically active country with a long history of destructive earthquakes – most recently in the 2015 Gorkha earthquake sequence. There have been substantial advances in the scienti-c understanding of earthquake hazard in Nepal, but it is not clear how that understanding has informed, or could inform, national and international investment in earthquake disaster risk reduction (DRR) activities, and to what effect. This paper aims to understand the role that earthquake science plays in DRR policy and practice in Nepal by seeking answers to the following. What earthquake science is used by DRR stakeholders in Nepal, and for what purpose? To what extent is earthquake DRR policy and practice in line with current scientific knowledge? Where and how is scientific knowledge seen as particularly useful for policy and practice, and where is it seen to be less useful and why? What are the drivers of and constraints on the production and use of earthquake science? Are there opportunities to better produce or broker scientific knowledge for policy and practice? What effects could better use of earthquake science deliver, and to whom?

Reflections on recent recommendations on the use of science in disaster risk reduction using case studies from Bangladesh and the Western United States.

Sargeant, S. L., and Lindquist, E., 2016.

The valuable role that science has to play in disaster preparedness and risk reduction is widely recognized and was highlighted during the development of the successor to the Hyogo Framework for Action for disaster risk reduction that was adopted in March 2015. However, there are many factors that limit how effectively science can inform both disaster risk reduction policy and practice. Understanding these factors and taking steps to overcome them require a broad view, and a comparative approach can be instructive. We focus on two projects that were independently completed by the authors: earthquake risk management in Bangladesh and flooding and wildfires management in the United States. We use each case to reflect on the implications of recent recommendations made by the Science and Technology Advisory Group (STAG) of the United Nations Office for Disaster Risk Reduction that attempt to increase the integration of science in disaster risk reduction policy making. We then use the STAG recommendations as a framework for integrating our independent case study findings. Despite the differences in the geographic contexts and hazards being considered, these examples broadly support the STAG recommendations. However, the fine details of the way in which science is used in decision making need to be given careful consideration if science is to fully support disaster risk reduction. Although our collective observations suggest that science is an important part of the disaster risk reduction (DRR) process, suggesting that it is “key to post-2015 DRR efforts” as the STAG recommendations do, may perhaps overstate the role that science is able to play.

Prospective Earthquake Forecasts at the Himalayan Front after the 25 April 2015 M 7.8 Gorkha Mainshock.

Segou, M and Parsons, T., 2016.

When a major earthquake strikes, the resulting devastation can be compounded or even exceeded by the subsequent cascade of triggered seismicity. As the Nepalese recover from the 25 April 2015 shock, knowledge of what comes next is essential. We calculate the redistribution of crustal stresses and implied earthquake probabilities for different periods, from daily to 30 years into the future. An initial forecast was completed before an M 7.3 earthquake struck on 12 May 2015 that enables a preliminary assessment; postforecast seismicity has so far occurred within a zone of fivefold probability gain. Evaluation of the forecast performance, using two months of seismic data, reveals that stress-based approaches present improved skill in higher-magnitude triggered seismicity. Our results suggest that considering the total stress field, rather than only the coseismic one, improves the spatial performance of the model based on the estimation of a wide range of potential triggered faults following a mainshock.

Frequency-magnitude Distribution for Natural and Mining-induced Seismicity in UK

Segou, M. and Baptie, B., 2016.

Over the last 30 years mining-induced seismicity in United Kingdom has been monitored by the British Geological Survey. About 4000 events with local magnitudes between -0.7 and 3.0 have been reported in coal mining reporting areas. The magnitude-frequency distribution follows a Gutenberg-Richter relation with a higher b-value of about 1.35 and 1.1 in Scotland and England, respectively. The above indicates the absence of large magnitude events for this type of induced seismicity. Within the instrumental seismicity period about 45% of seismicity corresponds to coal mining events. Reliable baseline for natural seismicity is essential to both discriminating from induced seismicity, such as hydraulic fracturing, and providing stake-holders/ decision makers real-time earthquake probabilities during operational phase. The magnitude-frequency distribution suggests a b-value of 0.85 with standard deviation of 0.12 for the entire catalog of naturally triggered events with some variability met at different regions. Analytically b-values of about 0.95, 0.70 and 0.9 are reported in Scotland, Wales and England with standard deviations of 0.1, 0.07 and 0.14, respectively. The 1984 Ml=5.4 Llyn Peninsula remains the larger earthquake reported the last half-century and it is characterized by a low p-value indicating a slow aftershock decay rate. In the UK a moderate sized event with magnitude larger than 5, occurs on average every 15 years followed by few (<10) felt aftershocks. In this low-seismicity environment only local population at the vicinity of mining fields has experienced light (EMS 5/6) ground shaking in the past.

Earthquake hazard assessment in Kazakhstan

Silacheva, N. and Mosca, I., 2016.

Engineers, architects and planners generally require something more specific to design their structures and infrastructure (including emergency plans) to be resilient to earthquakes. In particular, they need some estimate of likely ground motion or shaking at a particular place like a hospital or a school. This is usually expressed as maximum ground acceleration (peak ground acceleration, or PGA), which is what produces the forces that destroy buildings. Hazard assessments bring together knowledge from all the modern earthquake science techniques described in the previous sections to develop a picture of the likely distribution, size, character and frequency of occurrence of earthquakes. This picture can be very localised – to a particular active fault, or a place of particular interest – or it can be quite general, across a wide region. Its aim is to make a statement on the nature of the threat, not what can be done about it; nonetheless, it is the necessary first step for developing disaster-risk-reduction policies and strategies, and provides information needed by engineers, architects and planners.

Environmental Baseline Monitoring Project. Phase II, Final Report.

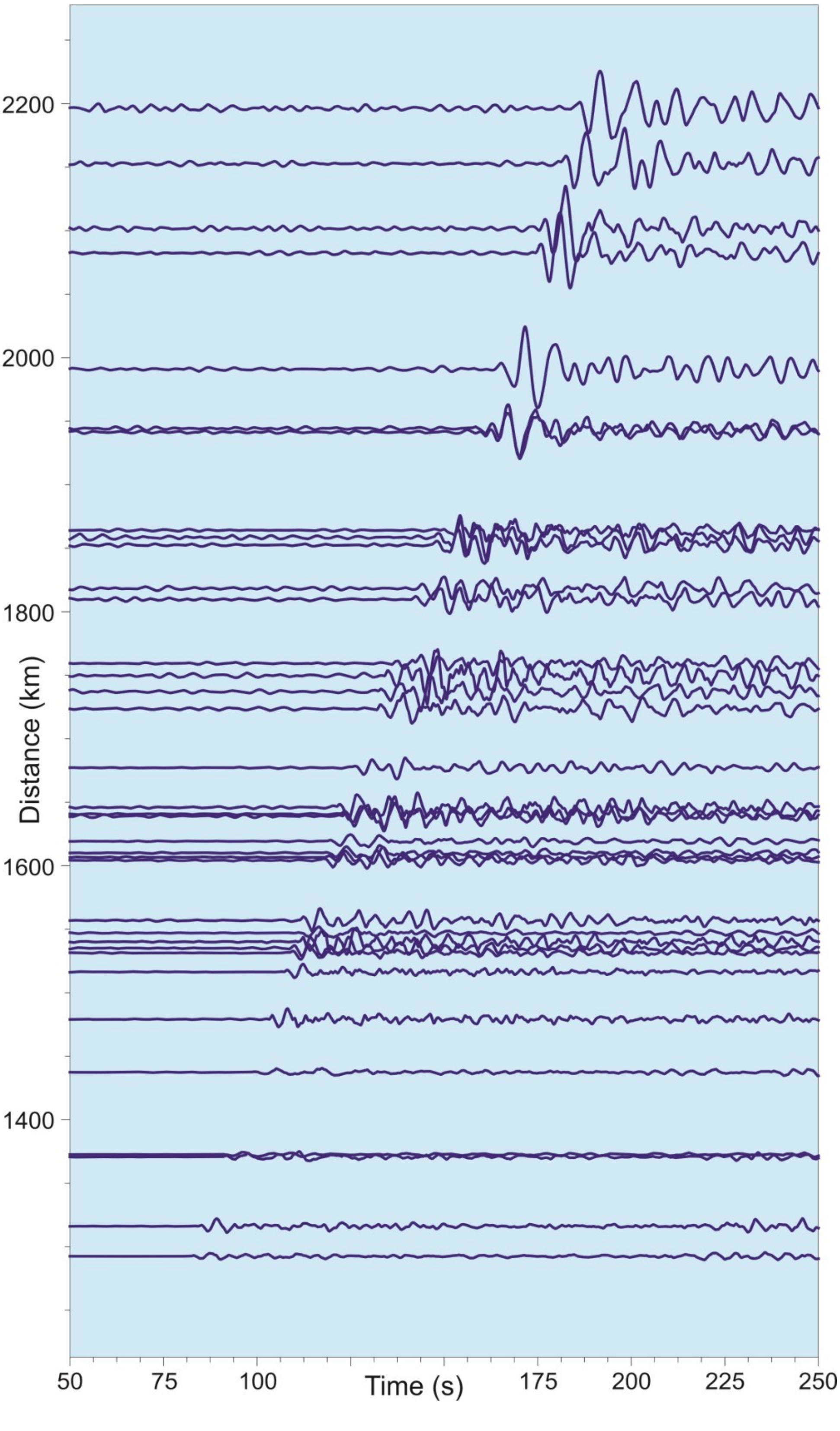
Ward, R.S., Smedley, P.S., Allen, G., Baptie, B.J., Daraktchieva, Z., Horleston, A., Jones, D.G., Jordan, C.J., Lewis, A., Lowry, D., Purvis, R.M. and Rivett, M.O., 2017.

This report is submitted in compliance with the conditions set out in the grant awarded to the British Geological Survey (BGS), for the period April 2016 – March 2017, to support the jointly-funded project "Science-based environmental baseline monitoring". It presents the results of monitoring and/or measurement and preliminary interpretation of these data to characterise the baseline environmental conditions in the Vale of Pickering, North Yorkshire and for air quality, the Fylde in Lancashire ahead of any shale gas development. The two areas where the monitoring is taking place have seen, during the project, planning applications approved for the exploration for shale gas and hydraulic fracturing. It is widely recognised that there is a need for good environmental baseline data and establishment of effective monitoring protocols ahead of any shale gas/oil development. This monitoring will enable future changes that may occur as a result of industrial activity to be identified and differentiated from other natural and man-made changes that are influencing the baseline. Continued monitoring will then enable any deviations from the baseline, should they occur, to be identified and investigated independently to determine the possible causes, sources and significance to the environment and public health. The absence of such data in the United States has undermined public confidence, led to major controversy and inability to identify and effectively deal with impact/contamination where it has occurred. A key aim of this work is to avoid a similar situation and the independent monitoring being carried out as part of this project provides an opportunity to develop robust environmental baseline for the two study areas and monitoring procedures, and share experience that is applicable to the wider UK situation. This work is internationally unique and comprises an inter-disciplinary researcher-led programme that is developing, testing and implementing monitoring methodologies to enable future environmental changes to be detected at a local scale (individual site) as well as across a wider area, e.g. 'shale gas play' where cumulative impacts may be significant. The monitoring includes: water quality (groundwater and surface water), seismicity, ground motion, soil gas, atmospheric composition (greenhouse gases and air quality) and radon in air. Recent scientific and other commissioned studies have highlighted that credible and transparent monitoring is key to gaining public acceptance and providing the evidence base to demonstrate the industry's impact on the environment and importantly on public health. As a result, BGS and its partners initiated in early 2015, a co-ordinated programme of environmental monitoring in Lancashire that was then extended to the Vale of Pickering in North Yorkshire after the Secretary of State for Energy and Climate Change (BEIS) awarded a grant to the British Geological Survey (BGS). The current duration of the grant award is to 31st March 2018. It has so far enabled baseline environmental monitoring for a period of more than 12 months. With hydraulic fracturing of shale gas likely to take place during late 2017/early 2018, the current funding will allow the environmental monitoring to continue during the transition from baseline to monitoring during shale gas operations. This report presents the monitoring results to April 2017 and a preliminary interpretation. A full interpretation is not presented in this report as monitoring is continuing and it is expected that there will be at least six months of additional baseline data before hydraulic fracturing takes place. This represents up to 50% more data for some components of the montoring, and when included in the analysis will significantly improve the characterisation and interpretation of the baseline. In addition to this report, the BGS web site contains further information on the project, near real-time data for some components of the monitoring and links to other projects outputs, e.g. reports and videos (www.bgs.ac.uk/research/groundwater/shaleGas/monitoring/home.html).

Micro-seismic source location with a single seismometer channel using coda wave interferometry

Zhao, Y., Curtis, A. and Baptie, B., 2016

Finding relative locations of seismic events is essential for discriminating earthquake fault and auxiliary planes from the sequences of aftershocks or foreshocks, studying earthquake interaction and recurrence, and monitoring stress state and induced (micro-)seismicity. Conventional methods, such as joint hypocenter determination and double-difference location, usually require a large number of seismic stations and good event-station azimuthal coverage to obtain reliable results. However, such requirements are not always fulfilled. To this end, a source location method based on coda wave interferometry (CWI) is developed, which uses the scattered waves in the coda of seismograms to estimate the differences between two seismic states, in this case to estimate the distance between pairs of earthquake locations. Those are then used jointly to determine the relative location of a cluster of events in a probabilistic framework. The purpose of this study is to test the performance of this novel approach on induced micro-seismicities, where it was applied to a micro-seismic dataset of mining induced events recorded in England. We find that source separation estimates are highly consistent and the earthquake location results agree to within estimated uncertainties when using different individual seismometer channels. We also discuss three issues that arose during the implementation for this dataset and provide solutions that can be used in future applications.



P-wave ground displacements from the magnitude 6 Amatrice earthquake on 24 August 2016 recorded at seismic stations across the UK. Traces are plotted in order of distance from the epicentre.