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Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Earthquake Seismology 2015/2016

BGS Seismic Monitoring and Information Service

Twenty-seventh Annual Report

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OPEN REPORT OR/17/032

Earthquake Seismology 2015/2016

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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 27th year of the project, one new broadband seismograph station was established, giving a total of 44 broadband stations. New strong motion instrumentation was also installed at an existing site. Real-time data from all stations are being 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 is generally low, less than one minute most of the time, and there is 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).

Eleven papers have been published in peer-reviewed journals. Two presentations were made at international conferences. Five BGS reports were prepared. We have continued to collaborate widely with academic partners across the UK and overseas on a number of research initiatives.

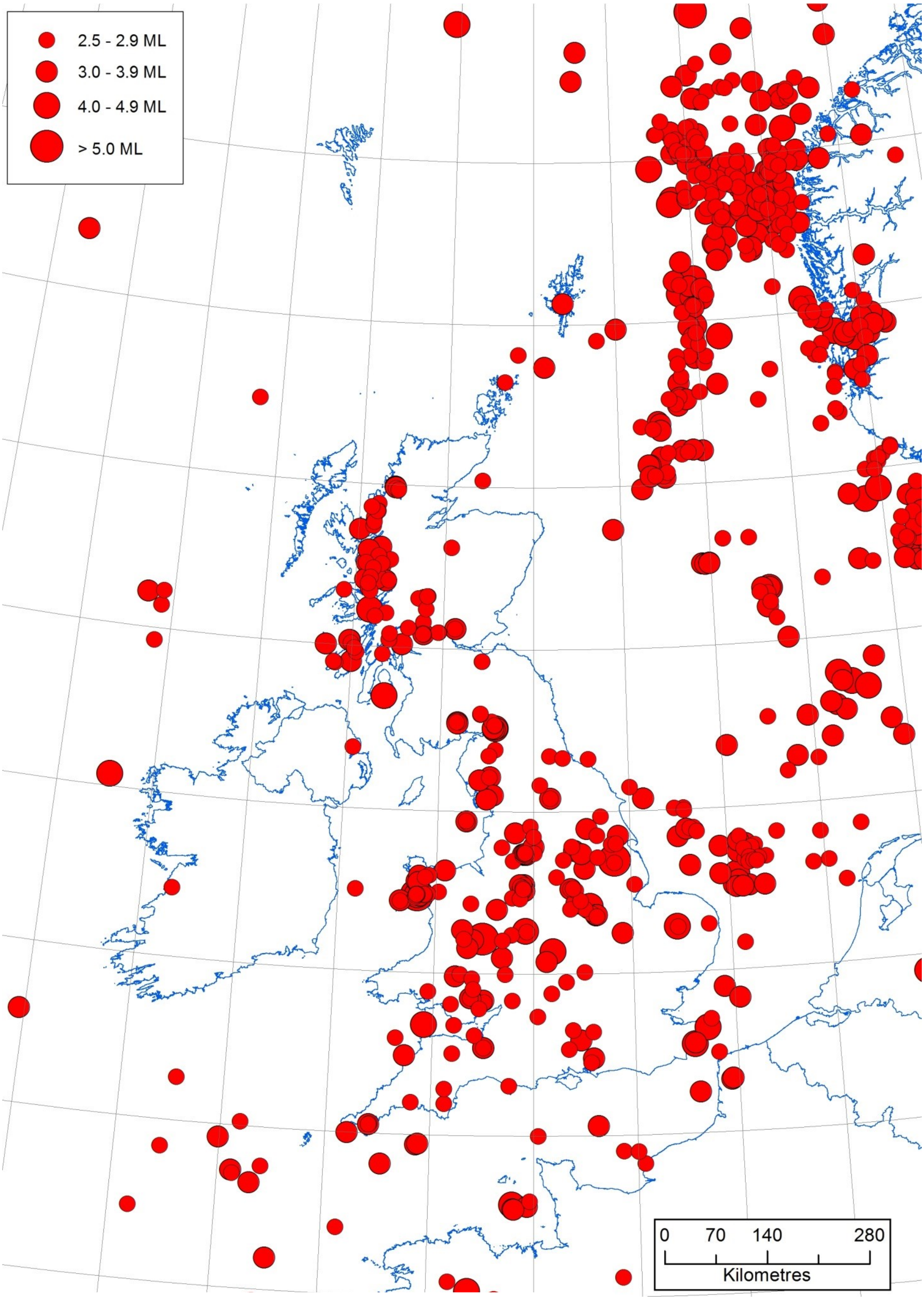
Introduction

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.

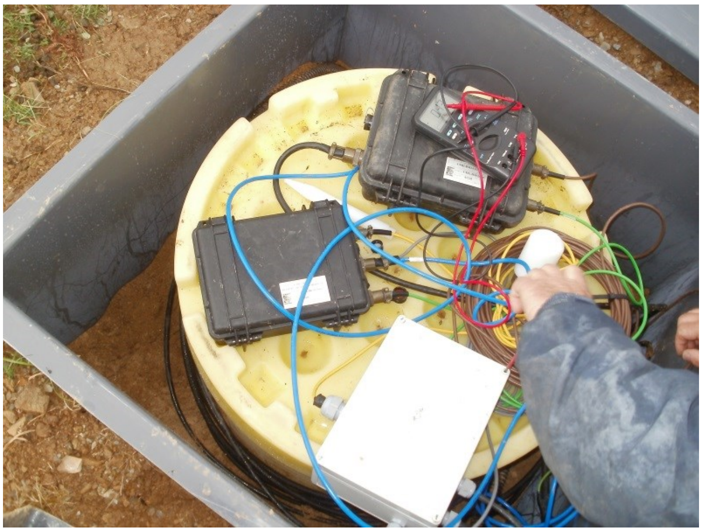
Almost every week, seismic events are reported to be felt somewhere in the UK. A small number of these prove to be sonic booms or are spurious, but a large proportion are natural or mining-induced earthquakes often felt at intensities which cause concern and, occasionally, some damage. The Information 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 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 in assessment of 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 2016.



Introduction

Monitoring Network

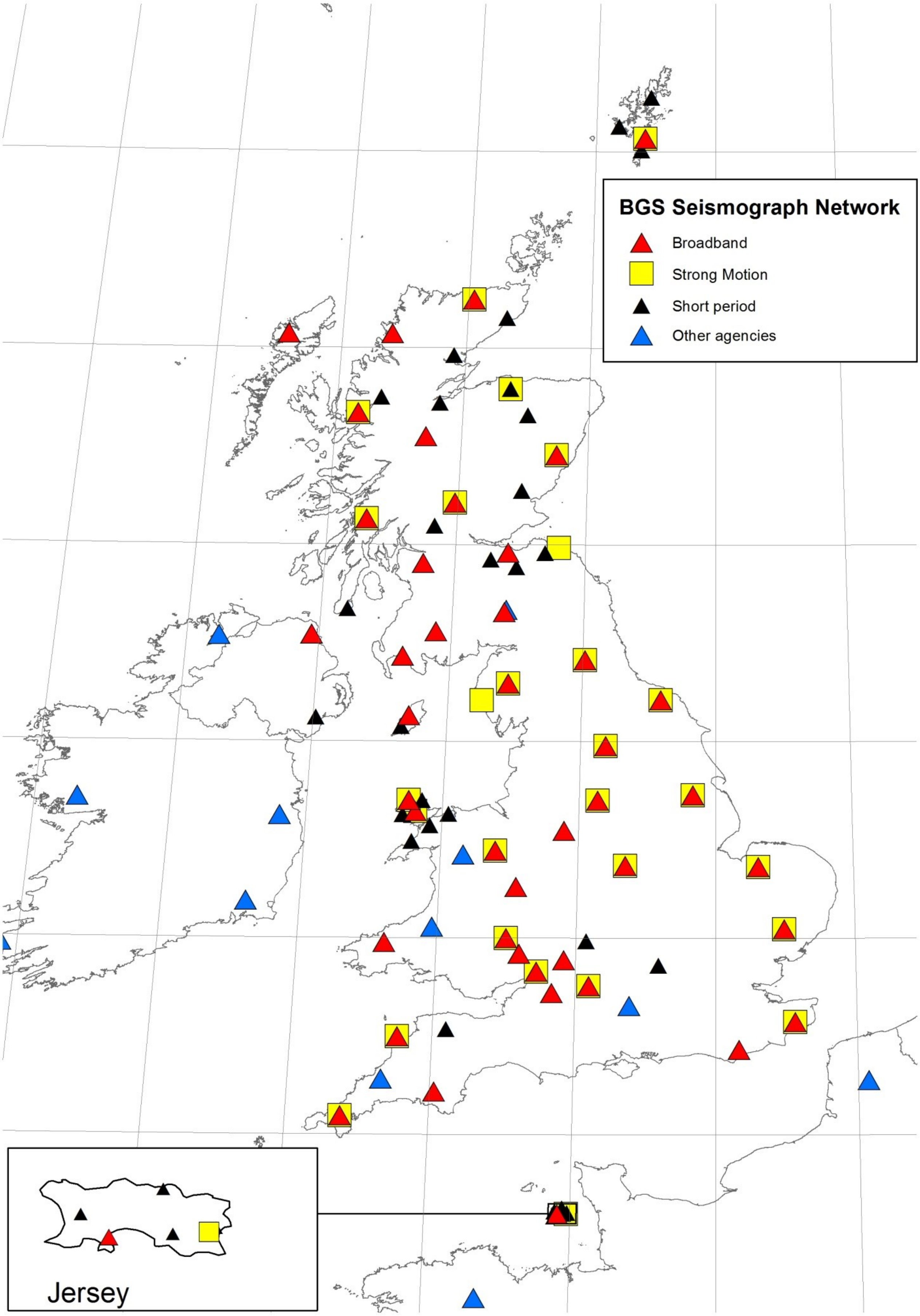
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late 1990s, the number of stations reached its peak of 146, with an average spacing of 70 km. We are now in the process 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 centred on Edinburgh, 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 nineties.

The network was divided into a number of sub-networks, each consisting of up to ten 'outstation' 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 response for 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 with our plans to upgrade the BGS seismograph network. Over the next few years we intend to develop a network of 40-50 broadband seismograph stations across the UK with near real-time data transfer to Edinburgh. These stations will provide high quality data with a larger dynamic range and over a wider frequency band for many years to come. So far, we have installed 44 broadband sensors at stations across the UK along with 30 strong motion accelerometers with high dynamic range recording for recording very large signals.



BGS seismograph stations, March 2016.

Achievements

Network Development

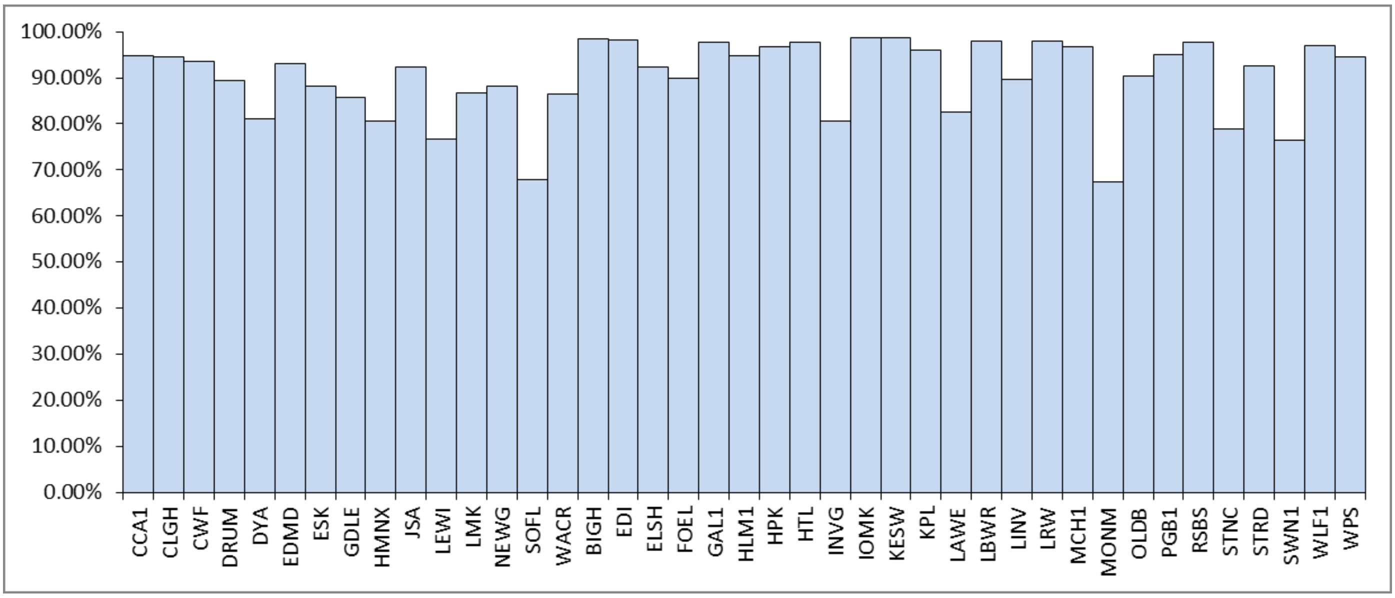
Broadband sensors with 24-bit acquisition are being deployed to improve the scientific value of the data and improve the services provided to customers. We continue to improve our near real-time data processing capability including the detection and location of significant seismic events in the UK and offshore area.

In the last year a new broadband stations was installed at Elmsett, Suffolk. This takes the total number of broadband stations operated by BGS to 44. Continuous data from all broadband stations are transmitted in real-time to Edinburgh, where they are used for analysis and archived.

A strong motion accelerometer was installed at Charnwood Forest, near Leicester. This instrumentation is designed to provide on-scale data for the largest expected earthquakes.

Two short period stations in the Lownet sub-network in southeast Scotland were decommissioned in the last year, along with another short period station at Shiel Bridge in the west of Scotland. This leaves twenty-nine operational short period stations across the UK. We expect this number to reduce further in future years. However, some short period stations will remain, such as those on Shetland and Jersey to ensure adequate detection capability. We now receive continuous real-time data from all short period stations.

Plans for a borehole sensor in northwest England have fallen through, despite having a borehole sensor for this. We hope to install this sensor at another site in the UK.

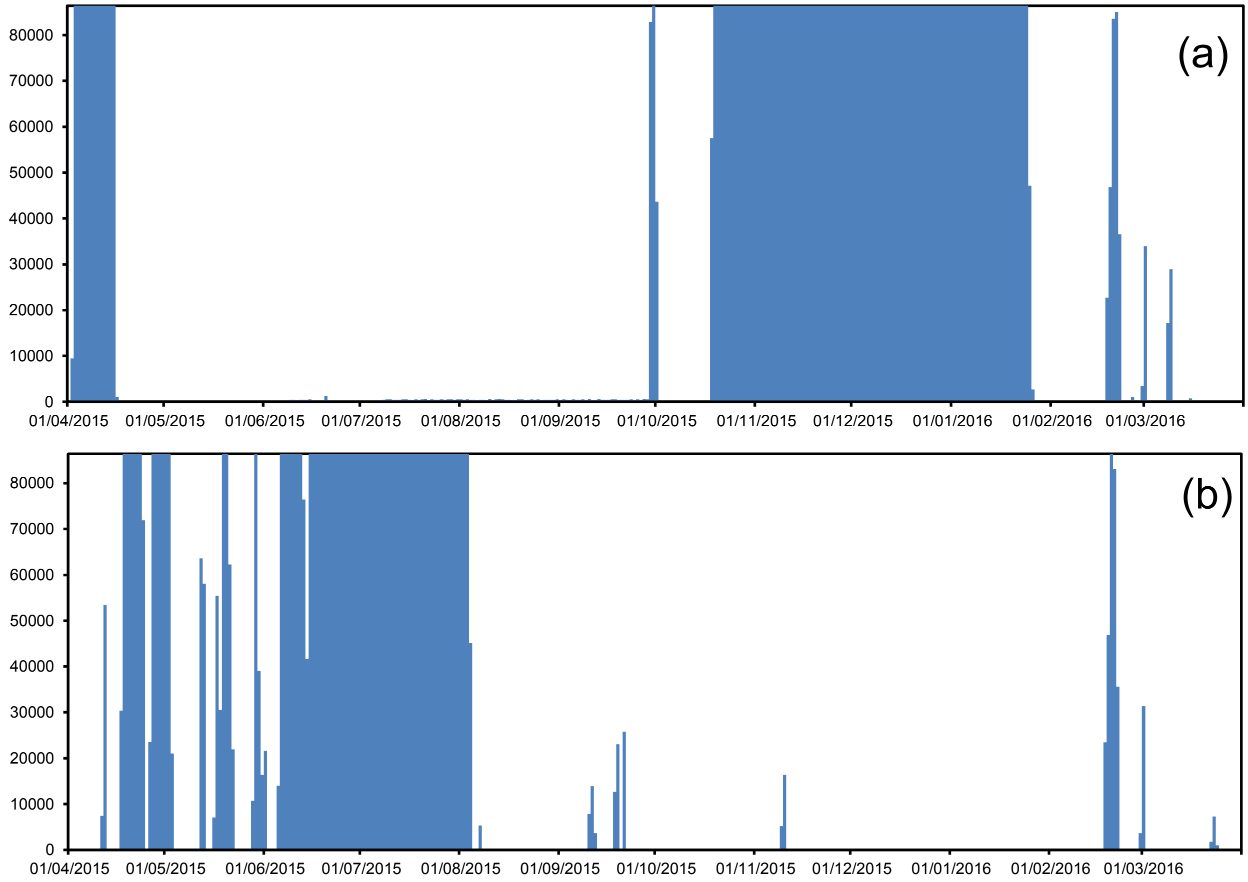


Data completeness for all broadband stations that operated throughout 2015-2016. Data are more than 80% complete for more than 90% of stations and more than 90% complete for over 60% of stations. Stations installed during the year are not included.

During the year, a total of 60 field trips were made to visit stations around the UK. Of these visits, 48 were for maintenance or fault repair, 4 were to carry out site surveys for new stations, 6 were for installation of new stations and 2 were for decommissioning of old stations.

Continuous data from all our broadband and all of our short period stations are now online within the BGS storage area network. The completeness of these data can be easily checked to gain an accurate picture of network performance. For 2015-2016, data are more than 80% complete for more than 90% of stations and more than 90% complete for over 60% of stations, both of which are slightly less than the previous year. 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 two worst performing stations, Monmouth (Monmouthshire) and Swindon returned 67% and 76%, respectively. In each case considerable downtime resulted from equipment failure due to lightning strikes that was concurrent with communications failures.

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 Dublin Institute of Advanced Studies, in Ireland, are vital for detection and location in a number of areas.



Data lost (number of seconds by date) for stations, (a) MONM (Monmouth) and (b) SWN1 (Swindon) which returned 67% and 76%, respectively.

Environmental baseline monitoring

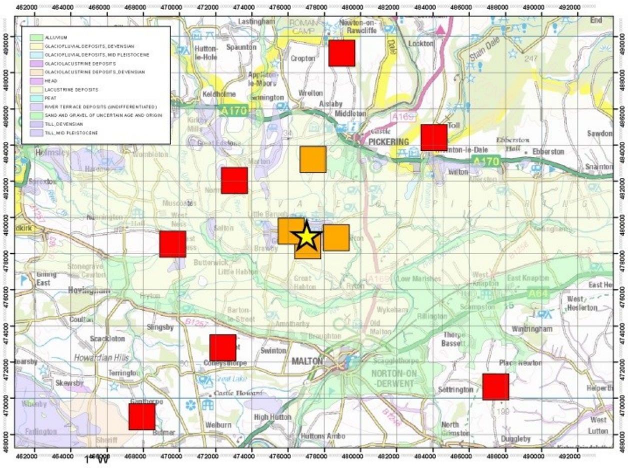
BGS, along with the universities of Birmingham, Bristol, Liverpool, Manchester and York, has initiated an independent environmental baseline monitoring programme in the Vale of Pickering, North Yorkshire (Ward, 2016). Part of this work involves the installation and operation of a network of seismic sensors to monitor background seismic activity in the vicinity of proposed shale gas exploration and production near Kirby Misperton.

Our aim 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.

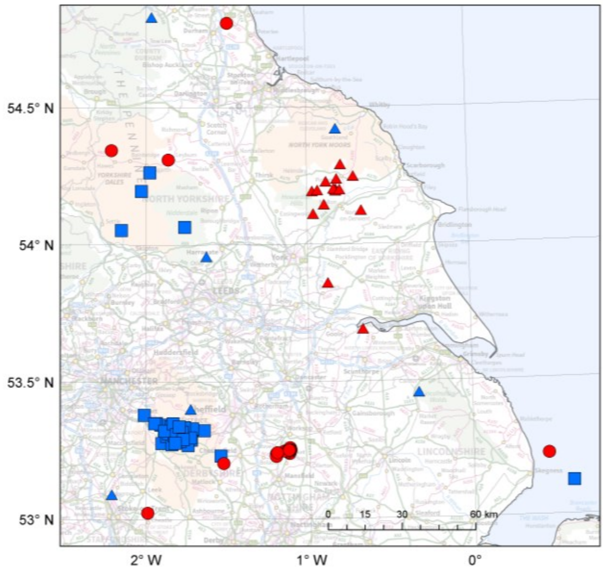
The monitoring network consists of eleven stations: four borehole seismometers close to the drill site; and seven additional sensors distributed radially around the site. The borehole instruments comprise of a downhole geophone or a downhole broadband seismometer. The sensors are situated at a depth of approximately 30 m below the surface and are all close to the Kirby Misperton drill site. Installing these instruments in boreholes should improve the signal-to-noise ratio of the recorded data and allow smaller events to be detected and located. This is particularly important for reliable detection and location of any small earthquakes that may be induced by hydraulic fracturing, as well as for the baseline monitoring.

The network is designed to reliably detect and locate any earthquakes with magnitudes of 0.5 and above across the region. In addition, it will allow us to detect and accurately locate possible induced seismicity close to the Kirby Misperton site with lower magnitudes.

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 simple detection algorithm is applied to the data from the Vale of Pickering stations as well as data from permanent BGS monitoring stations in the region to detect possible events.



Ordnance Survey map of the Vale of Pickering overlain by superficial geology. Red squares show the surface stations. The orange squares show the borehole sensors. The yellow star shows the location of the drill site.

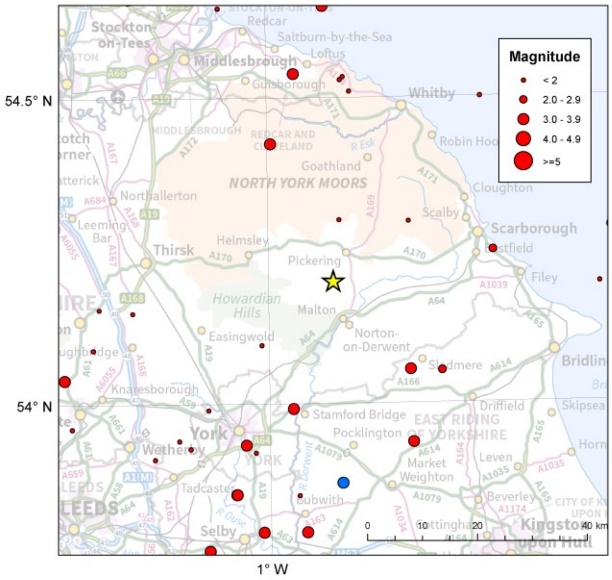


Seismic events detected by the Vale of Pickering stations and permanent BGS monitoring stations in the north east of England from 1/10/2015 to 31/3/2016. Red circles show earthquakes. Blue squares show events of a suspected explosive origin, e.g. quarry blasts or underwater explosions.

No events have been detected in the immediate locality of the Vale of Pickering, however, a number of other earthquakes and quarry blasts from elsewhere in the UK have been detected. These included thirty-one earthquakes, the largest of which was a magnitude 2.2 ML earthquake south of Worksop, Nottinghamshire. This earthquake was part of a sequence of 22 detected earthquakes in this area between 19 and 27 November 2015. Only one other earthquake with a magnitude of 2 or above was detected in northeast England in the monitored period. Forty-five events of a suspected explosive nature were detected, these are almost all quarry blasts, most of which originated from quarries in the Peak District. Six quarry blasts had magnitudes of 2.0 ML or above, the largest of which had a magnitude of 2.2 ML.

The Vale of Pickering region appears to be an area of low seismicity even for the UK with little significant recorded earthquake activity. Historically, the largest earthquake in the region was a magnitude 3.7 earthquake near Market Weighton in 1885. This had a maximum intensity of 5 EMS in the epicentral area, equivalent to shaking strong enough to cause buildings to tremble and top-heavy objects to topple. There have been a number of instrumentally recorded earthquakes in the region in the last 40 years with magnitudes in the range of 2-3 ML. These include: magnitude 2.9 and 3.0 ML earthquakes near Selby, North Yorkshire in 1978 and 1984, respectively; a magnitude 2.4 ML earthquake near Westerdale North Yorkshire in 1984; a magnitude 2.1 ML earthquake near Sledmere, Humberside in 1992; two earthquakes near York in 2003 and 2005 with magnitudes of 2.3 and 2.5 and, more recently, a magnitude 2.9 ML earthquake near Loftus, Cleveland in 2012. None of these earthquakes were within 20 km of Kirby Misperton.

Applying the UK average seismicity rate parameter to a 20 km by 20 km square, the size of the Vale of Pickering study region, suggests that there will be an earthquake with a magnitude of 2.0 or above only every 65 years, and three earthquakes with a magnitude of 0.0 or above every two years. This highlights the challenge of reliable estimation of background activity rates in low seismicity regions, since it may require many decades of baseline monitoring to reliably determine rates in small areas if the levels of natural seismicity are low.



Historical (blue circles) and instrumentally recorded earthquakes (red circles) from the BGS earthquake catalogue within a 100 km by 100 km square centred on the Kirby Misperton 8 well (yellow star).

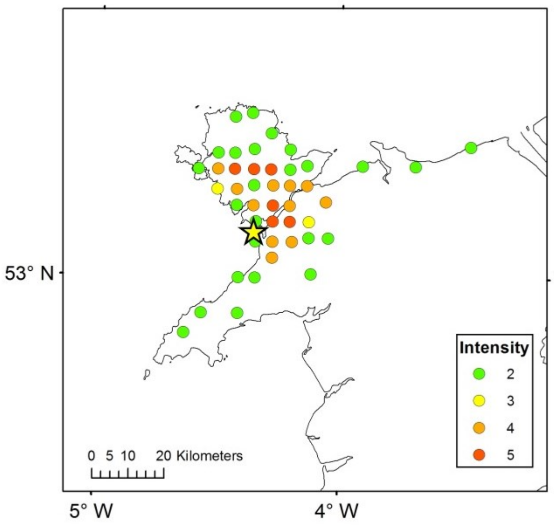
Achievements

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.

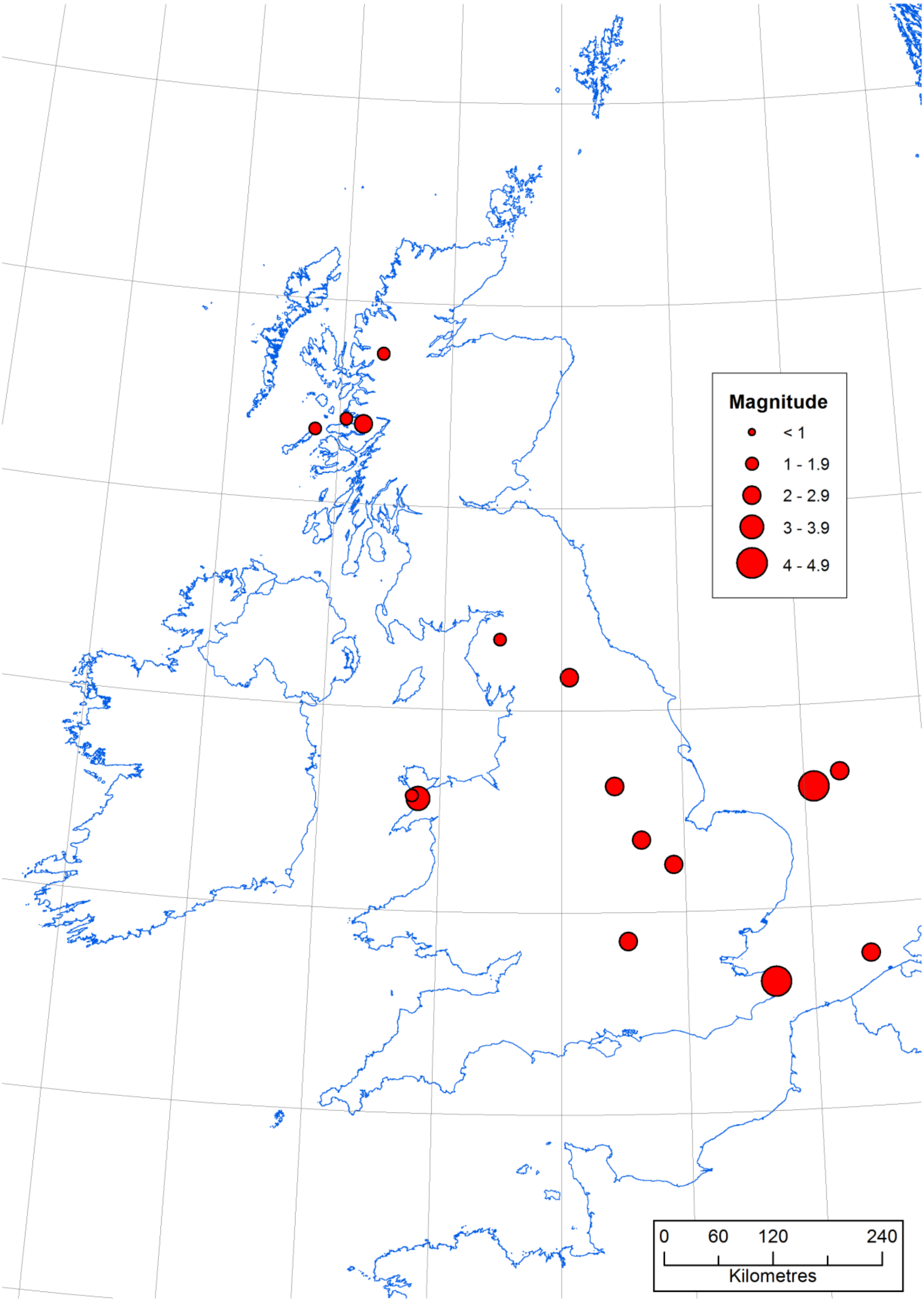
Notifications were issued for 19 UK events within the reporting period. Notifications for all local earthquakes were issued to Customer Group members within two hours of a member of the 24-hour on-call team being notified. The alerts include earthquake parameters, reports from members of the public, damage and background information. In addition, two enquiries were received from Nuclear Power Stations after alarms triggered. In each case, a response was given within 15 minutes.

We continue to update the Seismology web pages. These web pages are directly linked to our earthquake database to provide near real-time lists of significant earthquake activity, together with automatically generated pages for each event. This greatly simplifies the task of providing earthquake information and the details are updated whenever the event parameters change. The 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. This was used to collate and process macroseismic data for a number of events in the course of the year. We received over 1900 replies following the Ramsgate earthquake on 22 May 2015 (4.2 ML) and over 450 replies following the Caernarfon earthquake on 26 May 2015 (3.0 ML).



Macroseismic intensity data for the Caernarfon earthquake on 26 May 2015. Epicentre denoted by yellow star.

Data from the questionnaires are grouped by location into 5x5 km squares using postcodes and an intensity value is assigned to each square, given at least five responses are received from any square. Where fewer responses are received (especially the case in sparsely populated areas) the intensity is either given as “felt” or “not felt” (which are defined as intensity 1 and 0, respectively). These data are processed automatically to produce the macroseismic maps for the seismology web pages.



Events in the reporting period (1 April 2015 – 31 March 2016) for which alerts have been issued. Circles are scaled by magnitude.

Achievements

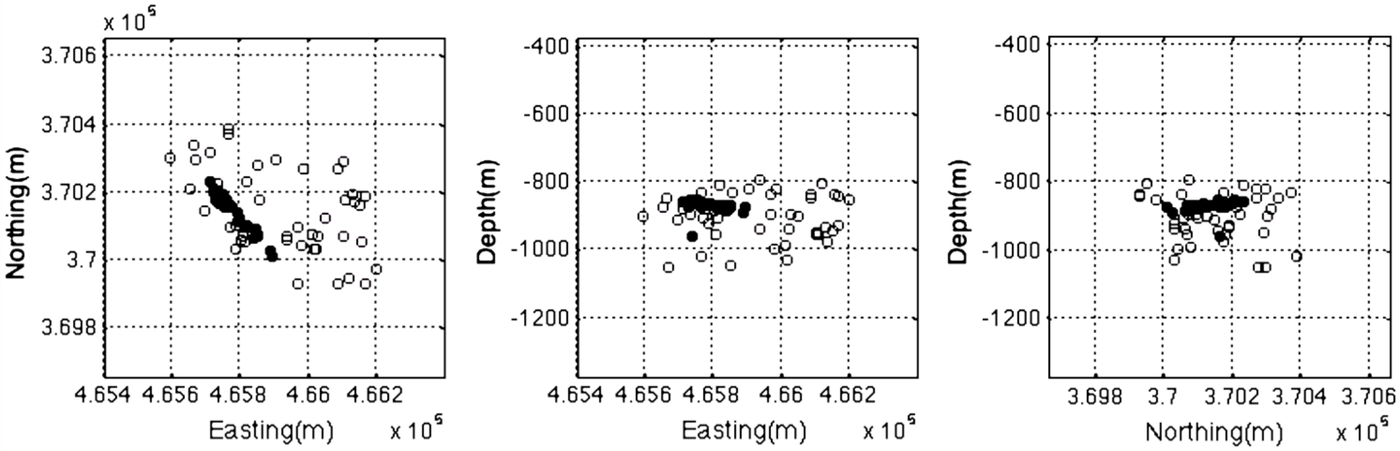
Collaboration and Data Exchange

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

A PhD student at Edinburgh University, funded partly by BGS, is exploring the use of coda wave interferometry for seismic event location, including analysis of changes in both earth properties and seismic event locations. In particular, the student is investigating how such methods might be used to provide robust seismic event locations when only sparse data are available. The work will also include the development of new processing methodologies that can be applied to real-time seismic data.

A BGS CASE student at the University of Cambridge is continuing her PhD research into the causes of regional uplift in the British Isles. During this project an array of seismometers has been deployed across Scotland to provide data for a detailed investigation of the Earth's Crust and Upper Mantle under the northern part of the British Isles. Thinner crust beneath northwest Scotland may suggest that present-day topography is maintained by regional dynamic support, originating beneath the lithosphere.

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, which runs from 2012-2017. 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. Susanne has also recently started 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.



CWI single station locations (open circles) and multi-station double difference locations (black circles) for the 2014-2015 Ollerton mining earthquake sequence.

Margarita Segou is working 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.

Margarita Segou is also working with researchers from the Institute of Statistical Mathematics, Tokyo, Japan in order to constrain using seismicity models the post-Tohoku stress recovery stressing rates of inland Japan.

In another project, Margarita Segou is working with researchers from the US Geological Survey to develop an alternative hypothesis to the question of earthquake triggering. This should enhance our ability to predict earthquakes in tectonically active regions in the vicinity of geothermal fields. The study is expected to have an important impact on understanding how the static stress field affects the evolution of aftershock sequences.

Ilaria Mosca is working within the Earthquakes without Frontiers project 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.

In September 2015, Heiko Buxel assisted researchers from University College Dublin to install two small seismic arrays immediately east of Vatnajokull in Iceland, close to the Laki volcanic system. This work was carried out as part of FUTUREVOLC, a 26-partner project funded by FP7 Environment Programme of the European Commission, whose aim is to conduct long-term monitoring in geologically active regions of Europe prone to natural hazards.

BGS data are exchanged with other agencies to help improve source parameters for regional and global earthquakes. Phase data are distributed to the European-Mediterranean Seismological Centre (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 484 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.

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 our “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. This year we have added 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 1,553,000 visitors logged in the year (over 13.3 million hits). Significant peaks (up to ten times the daily average) were observed following the Ramsgate earthquake of 22 May 2015, and the Caenarfon earthquake (May 2015).

We actively use Twitter, Facebook, Audioboo and YouTube to post earthquake alerts, to 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

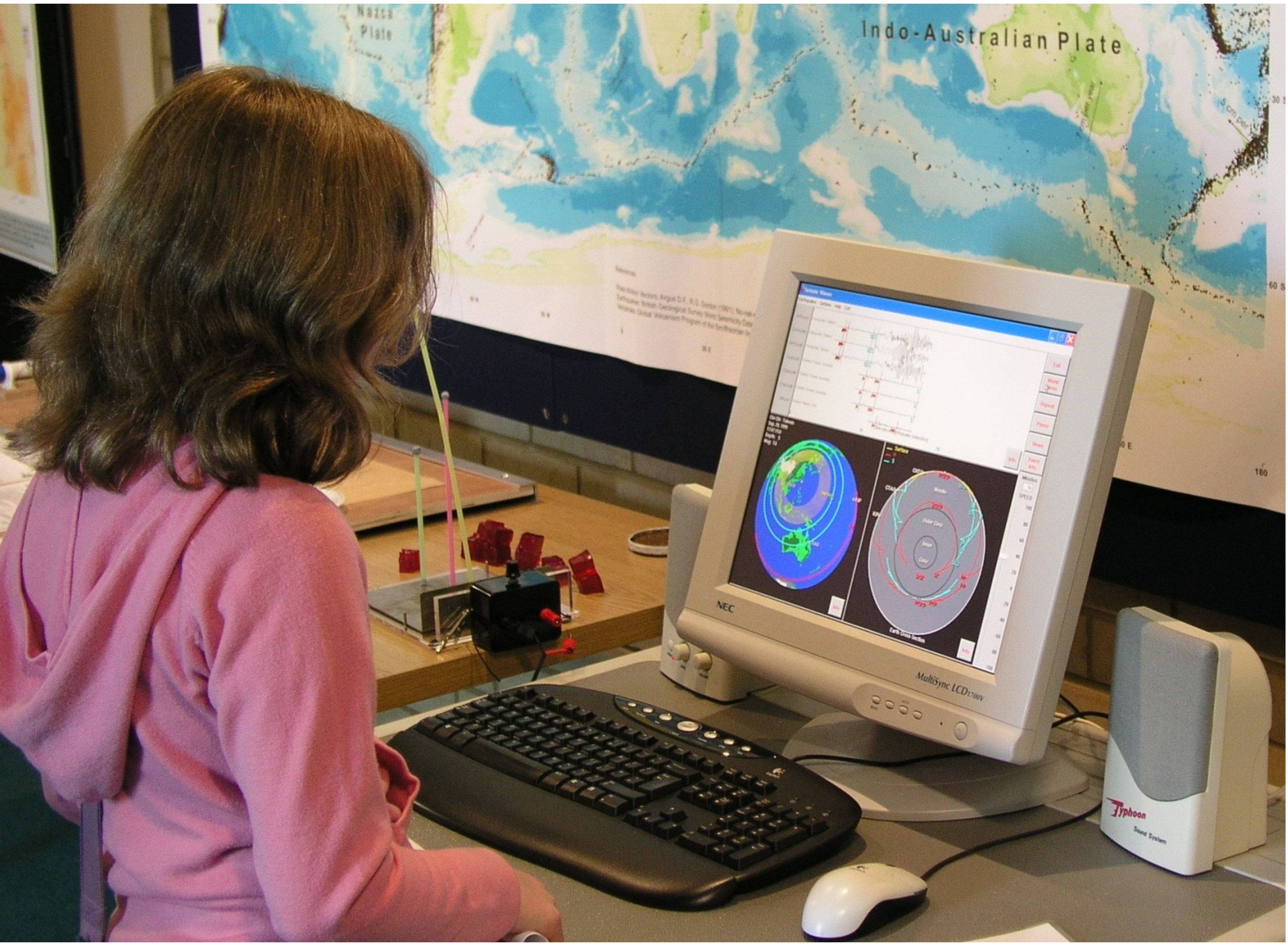
The SEP seismometer used in the School Seismology Project.

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.

BGS assisted the National Science Learning Centre to develop a Continuing Professional Development (CPD) course for teachers on "Earthquakes and other Natural Hazards" which has now run (with assistance from UKSSP staff) at three separate Science Learning Centres, receiving excellent feedback from teachers attending.

A second tranche of funding for the UKSSP has been won from the Petroleum Exploration Society of Great Britain, which will enable partnerships with eight university earth science departments across the UK to continue the roll out of resources to new schools.

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 2015-2016, at least 696 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.



Seismic Activity

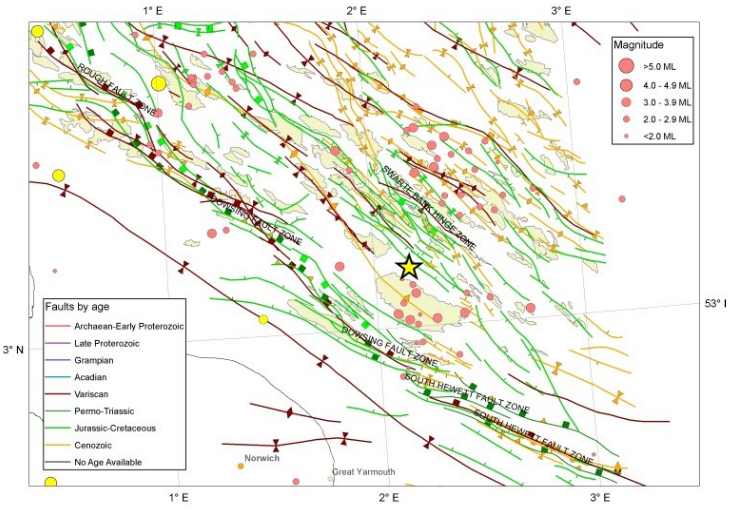
The details of all earthquakes, felt explosions and sonic booms detected by the BGS seismic network have been published in monthly bulletins and compiled in the BGS Annual Bulletin for 2015.

There were 252 local earthquakes located by the monitoring network during 2015-2016, with 29 having magnitudes of 2.0 ML or greater, and eight having magnitudes of 3.0 ML or greater. Ten events with a magnitude of 2.0 ML or greater were reported felt, together with a further ten smaller ones, bringing the total to 20 felt earthquakes in 2015-2016.

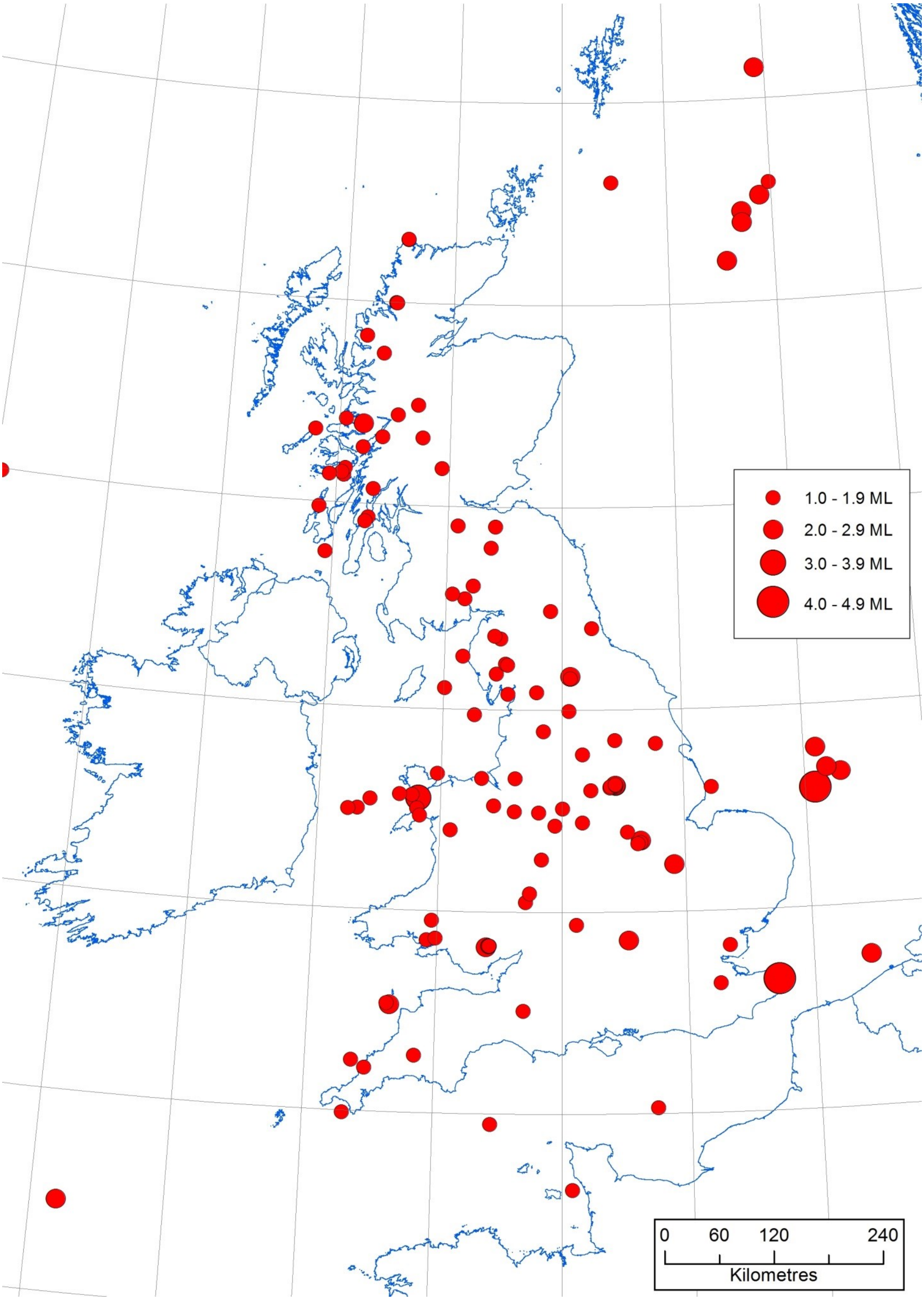
The largest earthquake in and around the British Isles during 2015-2016 was a magnitude 4.2 ML event near Ramsgate. The earthquake occurred on 22 May 2015 at 01:52 UTC, with an epicentre approximately 5 km SSE of Ramsgate, Kent. The earthquake was widely felt across southeast England and Belgium with a maximum observed intensity of 5 EMS. This was the largest earthquake to have occurred in the vicinity since a magnitude 4.3 ML earthquake at Folkestone on 28 April 2007.

A magnitude 3.0 ML earthquake occurred on 26 May at 15:41 UTC near Caernarfon, off the northern coast of the Lleyn Peninsula, Gwynedd, approximately 21 km WSW of the magnitude 5.4 ML earthquake that occurred on 19 July 1984, the biggest ever recorded onshore in the UK. Three aftershocks were recorded between 29 and 31 May, with magnitudes of 1.7, 0.8 and 1.7 ML, respectively, all of which were reported as having been felt by only a couple of people.

A magnitude 4.1 ML earthquake was recorded in the southern North Sea on 06 August 2015 at 15:03 UTC, with an epicentre approximately 72 km northeast of Great Yarmouth, Norfolk. The earthquake was felt on nearby oil platforms in the Leman Alpha field, where platforms were observed to sway. It was also felt in Sheringham and Hickling on the Norfolk coast.



Location of the magnitude 4.1 ML earthquake in the southern North Sea on 06 August 2015 (yellow star). The coloured lines show mapped faults in the region.



Epicentres of all earthquakes in and around the UK detected in the reporting period (1 April 2015 – 31 March 2016).

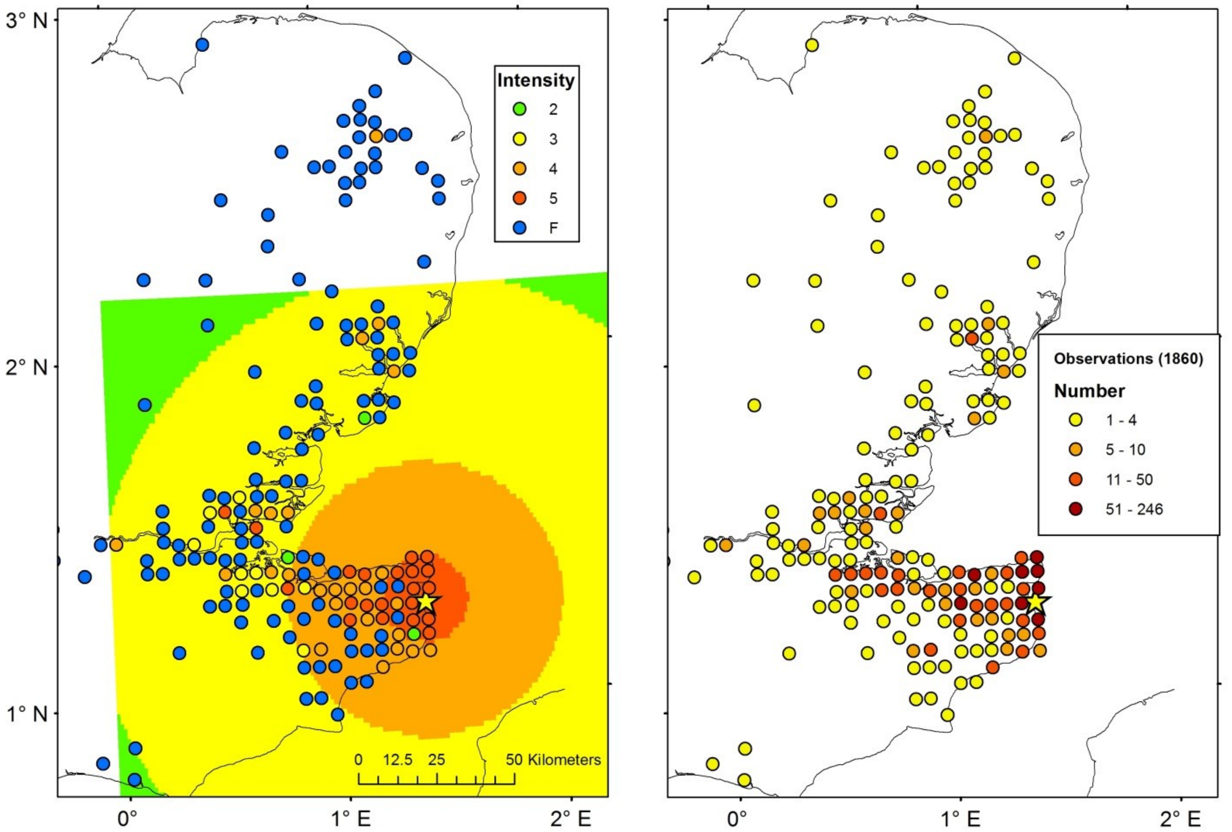
Seismic Activity

The Ramsgate Earthquake

Significant media and public interest was aroused on 22 May 2015 following a magnitude 4.2 ML near Ramsgate, Kent. The earthquake was widely felt across southeast England with a maximum observed intensity of 5 EMS.

The earthquake occurred on 22 May 2015 at 01:52 UTC, with an epicentre approximately 7 km south of Ramsgate, Kent. The instrumental magnitude was determined at 4.2 ML, and initial reports suggested that the earthquake had been felt widely across southeast England. This was the largest earthquake to have occurred in the vicinity since a magnitude 4.3 ML earthquake in Folkestone on 28 April 2007.

Over 1,900 members of the public from 402 different postcodes completed our online macroseismic questionnaire, allowing EMS intensity to be calculated in different locations. A maximum intensity of 5 EMS was observed in and around Ramsgate and Margate, close to the epicentre, while intensities of 4 EMS were observed as far away as Chatham, Kent and Southend-on-sea in Essex. The earthquake was felt at distances of up to 175 km from the epicentre, particularly across Kent, Suffolk and Norfolk. The earthquake was also widely felt in Belgium,



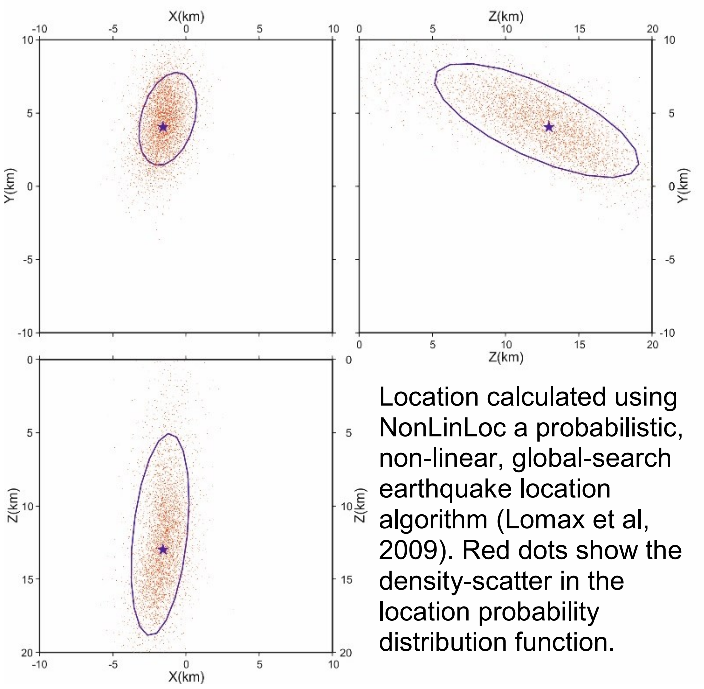
Small coloured circles in the left hand map show intensities calculated from macroseismic data. Also shown are modelled intensities (shaded areas) calculated using the intensity-distance relationship of Musson (2005). The right hand map shows the number of observations used to determine each intensity value. Over 1900 questionnaires from 402 different postcode locations were collected for the earthquake.

on the other side of the English Channel, where the maximum observed intensity was 3 EMS.

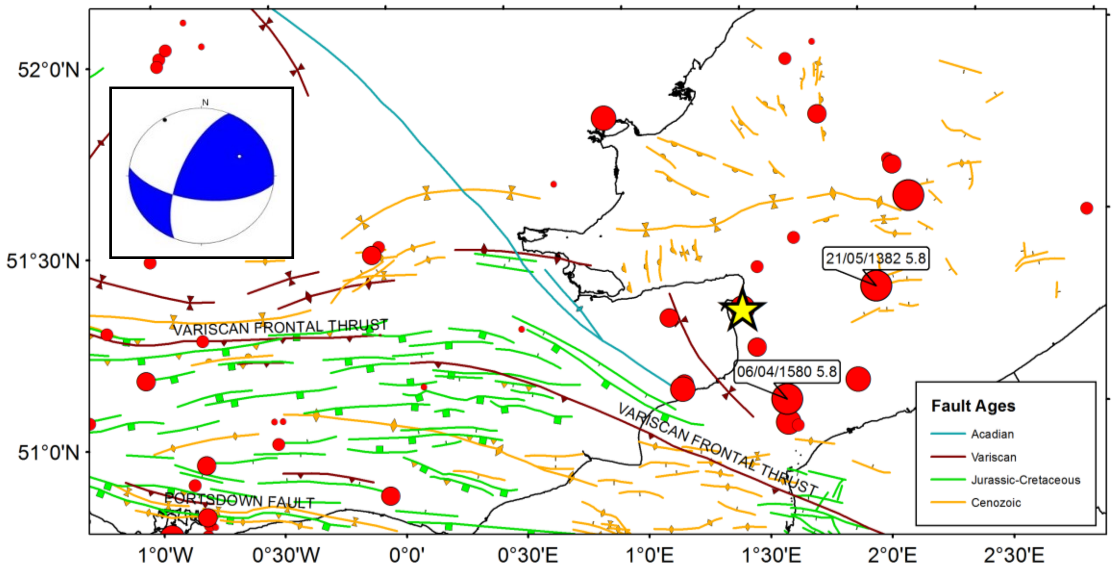
Almost all of the reports indicated that people were awoken from their sleep. Over half the reports described the shaking strength of the earthquake to be moderate, mainly with a trembling effect, and described the sound strength as moderate. Over two thirds of the reports stated that windows rattled and one third reported furniture shaking.

A moment magnitude of 3.6 Mw was calculated from observed S-wave displacement spectra recorded at a range of distances using the method of Ottemoller and Haskov (2003). The average attenuation model of Sargeant and Ottemoller (2009) was used to correct for attenuation along the path. The result is significantly less that the value of 3.8 obtained by conversion of the local magnitude (4.2 ML) using the relationship of Grunthal et al (2009). Peak ground accelerations 18 mm/s^2 were recorded at distances of 30 km from the epicentre.

A focal mechanism was determined for the Ramsgate earthquake of 22 May 2015 using data recorded from across the UK and northern Europe. Our solution shows oblique strike slip faulting along either a north-northeast south southwest striking fault, dipping steeply in a westerly direction, or east southeast west north west striking fault plane, dipping to the south. The latter orientation is reasonably consistent with the observed trend of major Variscan fault structures that are observed in southern Britian. However, given the small extent of the ruptured area (~1 km^2), it is difficult to accurately map earthquakes to specific faults, particularly at depth, where the fault distributions and orientations are unclear.



Location calculated using NonLinLoc a probabilistic, non-linear, global-search earthquake location algorithm (Lomax et al, 2009). Red dots show the density-scatter in the location probability distribution function.



Observed faulting in the vicinity of the epicentre (yellow star). Faults are coloured by age. The red circles show recorded seismicity in the area.The inset shows the focal mechanisms calculated using Snoke et al (1984).

Seismic Activity

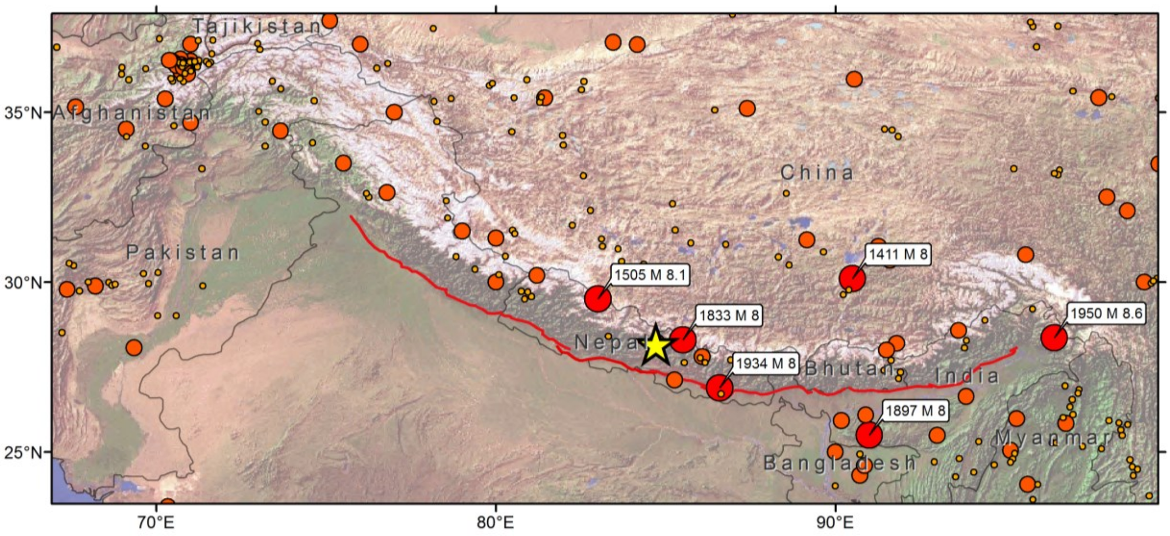
Overview of global earthquake activity

Worldwide, there were nineteen earthquakes with magnitudes of 7.0 or greater and 146 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 the Gorkha earthquake in Nepal on 25 April, 2015 and the Illapel earthquake in Chile on 16 September, 2015.

The Mw 7.8 Gorkha, Nepal, earthquake on 25 April 2015 caused over 9,000 deaths and left hundreds of thousands without shelter. The earthquake ruptured a 140 km long segment of the Main Himalayan Thrust (MHT) from Gorkha, in the west of Nepal, towards Kathmandu (Elliot et al, 2016).

Seismic hazard in the region is high and a number of large earthquakes have occurred along the Himalayan Arc in the last few hundred years (e.g. Chen and Molnar, 1977). In 1833 an earthquake with a magnitude of at least 7.7 devastated the Kathmandu valley. The magnitude 8.1 Nepal-Bihar earthquake of 1934 resulted in more than 10,000 deaths and caused heavy damage in Bihar State (India) and eastern Nepal. Kathmandu was strongly affected. The Gorkha earthquake occurred in a seismic gap between the 1905 Kangra earthquake (M 7.8) in the west and the1934 Nepal-Bihar earthquake in the east.

Although the number of casualties was large, it was rather less than might have been expected, given the location and magnitude of the earthquake, the directivity of the rupture, and the vulnerability of many of the of local buildings. This may be explained by the nature of the ground motions, which were dominated by energy at periods significantly longer than the resonant periods of many buildings (Martin et al, 2015).



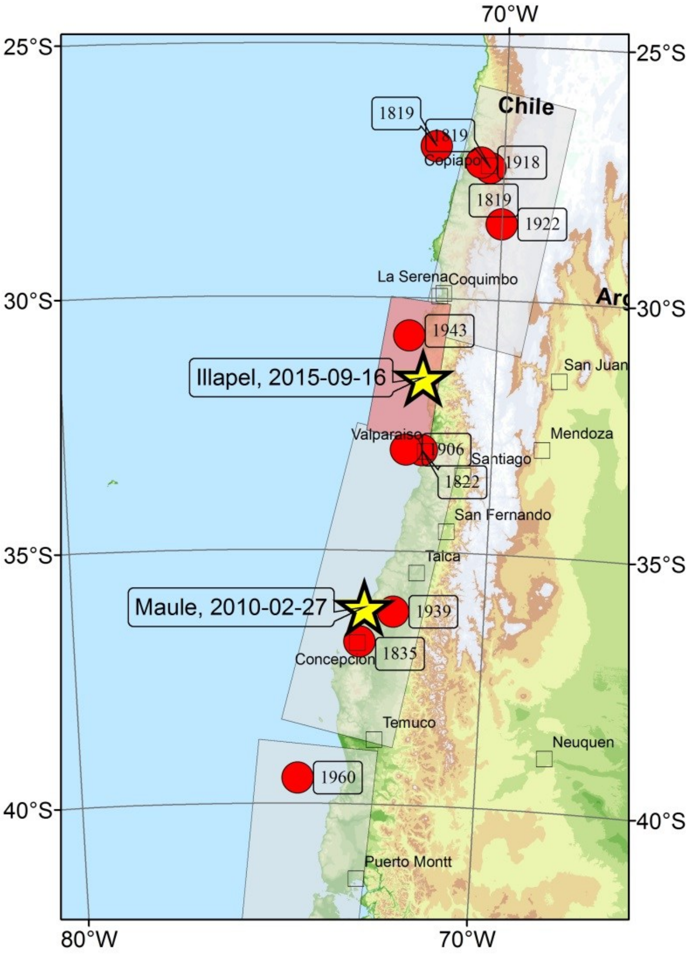
Historical seismicity of the Nepal region (red circles) along with the location of the Himalayan Frontal Thrust (red line), which maps the plate boundary between India and Eurasia. The epicentre is denoted by a yellow star.

On 16 September 2015, a magnitude 8.3 earthquake occurred near Illapel in Coquimbo region of Chile, approximately 250 km north-northwest of Santiago. The thrust earthquake was a result of the subduction of the Nazca plate beneath the South America plate, forming the well-known Peru-Chile Trench.

Large destructive earthquakes have occurred along this trench throughout historical times, with more than 15 M7+ seismic events at a distance of 400 km from the epicentre of this most recent earthquake. Among them the largest recorded global earthquake, a magnitude 9.5 earthquake in 1960.

The September 2015 earthquake ruptured a ~250 km segment of plate boundary between the Nazca and South American plates stretching roughly between Valparaiso and Coquimbo (the red hatched area on the map). This is immediately north of the segment that ruptured in the magnitude 9.0 Maule earthquake in 2010, and immediately south of a historic magnitude 8.5 in 1922. The Maule earthquake killed over 500 and caused extensive damage, with several hundred thousand buildings destroyed.

Reports suggest that the epicentral area near Illapel (southern Coquimbo region) experienced severe to violent shaking, however, the number of casualties was low, with the Chilean government reporting 13 deaths. Much of the population in the region reside in structures that are resistant to earthquake shaking, though some vulnerable structures do exist.



Historical earthquakes in Chile. The yellow stars show the locations of the Maule and the Illapel earthquakes in 2010 and 2015. The shaded polygons show approximate rupture areas for the 1819, 1960, 2010 and 2015 earthquakes.

The historic behaviour will continue into the future, with further very large (in excess of magnitude 8) earthquakes along this plate boundary.

Scientific Objectives

Strain rate and seismicity in Britain and Ireland

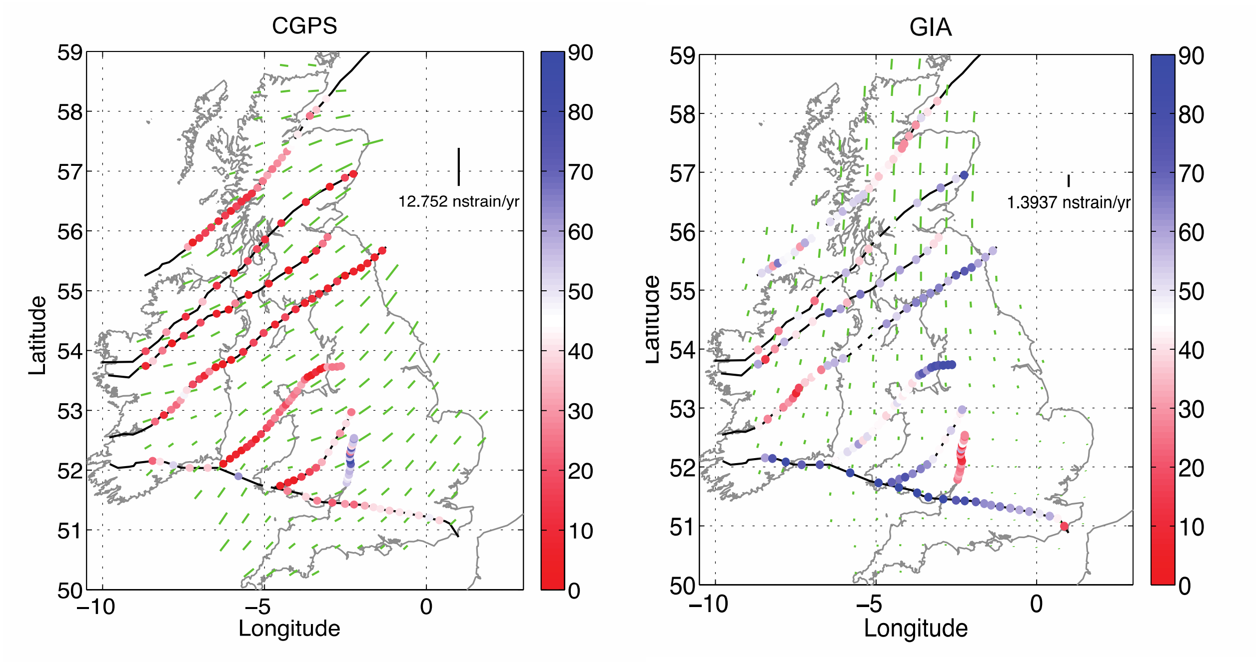
Velocities measured by a network of Continuous Global Positioning System (CGPS) stations have been used to calculate a 2D strain rate tensor field. The CGPS derived strain rate field exhibits predominantly left-lateral strike-slip loading occurring along a NE-SW trend and is consistent with present-day tectonic stresses arising from N- to NNW-directed horizontal compression. This trend matches the recent geological history of the large-scale faulting structure in Britain and Ireland where Alpine-related compression has played a major role in faulting.

Analysis of long-term velocity trends derived from global positioning systems stations can provide insight into active deformation at regional scales (e.g. D'Agostino et al., 2008). Murphy et al (2016) use crustal velocities derived from a CGPS network distributed across Britain and Ireland (Teferle et al., 2009) to calculate the current strain rate in this region for the first time. A strain rate field for a Glacio-Isostatic Adjustment (GIA) model (Spada et al., 2004) is calculated using the same method. The two strain rate fields were compared with major fault systems and recorded seismicity in order to investigate the underlying nature of the current seismicity and strain accumulation in Britain and Ireland.

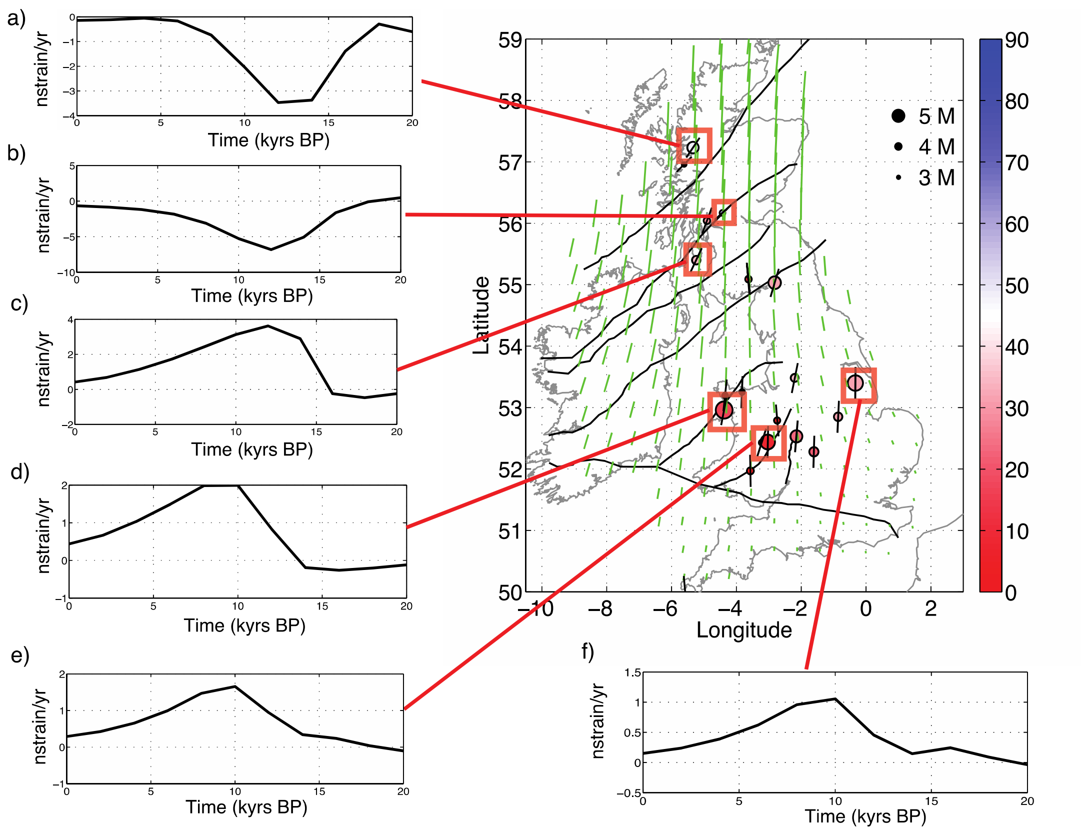
The CGPS derived strain rate field exhibits predominantly left-lateral strike-slip loading occurring along a NE-SW trend and is consistent with present-day tectonic stresses arising from N- to NNW-directed horizontal compression. This trend matches the recent geological history of the large-scale faulting structure in Britain and Ireland where Alpine-related compression has played a major role in faulting. Analysis of strike-slip focal mechanism data shows the strike of left lateral mechanisms in Scotland aligns with the left lateral plane of the CGPS strain rate. This correlation breaks down moving south, particularly in Wales where the fault strike of strike-slip earthquakes differs by up to 85° compared to the corresponding CGPS strike-slip loading axes.

By contrast, the strain rate derived from the GIA simulation provides left-lateral loading along a N-S trend. This differs from the NE-SW trend observed in the CGPS data and is poorly orientated in relation to loading of large-scale geological structure in Britain and is an order of magnitude smaller than the CGPS strain rate. The GIA strain rate is poorly aligned with the strike-slip seismicity in Scotland but it does provide loading for strike-slip events in Wales and has done so for the last 18,000 years. This implies that seismicity in Britain is driven by two different sources affecting two different sets of faulting: tectonic stresses are driving NE-SW strike-slip seismicity and GIA contribute in triggering N-S/E-W trending seismicity.

Comparing seismic and geodetic moment release rates shows that this deformation is predominantly aseismic.



Left lateral loading orientation derived from (a) CGPS velocities and (b) GIA. Green lines represent the maximum shear strain rate vectors in terms of left lateral loading rates. Black lines denote major faults, dots on the lines represent the angle between optimum left lateral loading by the stain rate field and the local strike of the fault.



Comparing left lateral fault solution from fault mechanism solutions [Baptie, 2010] with the left lateral strain rate due to GIA. Symbols have same representation as in the figure above: dots represent earthquakes, the colour of the dot is the difference between the strike based on the focal mechanism solution for left lateral strike slip and the GPS derived left lateral strain rate.

Earthquake Scenarios in the Tien Shan

Recent studies have identified surface ruptures associated with historical and paleoseismological earthquakes that occurred in the central segment of the Tien Shan. We use these findings to calculate ground shaking based on realistic fault rupture models and assess the potential impact in Almaty. The results are compared with the results published for the Global Earthquake Model (GEM) allowing the different scenarios to be associated with a frequency of occurrence.

The central segment of the Tien Shan ranges was the scene of devastating historical earthquakes between the end of the 19th century and the beginning of the 20th century (i.e. 1887, 1889, and 1911). Almaty, the former capital of Kazakhstan and the largest city in the region, was badly damaged by every event due to its proximity to their epicentre area. At that time, Almaty was thinly populated, but nowadays it has a population of about 1,700,000. This highlights the vulnerability of the city if similar earthquakes occur again.

We used realistic fault rupture models together with ground motion predictive equations (GMPEs) to calculate ground motions across a grid for the area of interest. The ground motion values sample the aleatory uncertainties in the GMPE by choosing at random a ground motion value within three standard deviations of the median prediction. To set a stable scenario, we iterate the procedure 5000 times and therefore simulate 5000 scenarios for each ground motion field. Then, we compute the average and the standard deviation of the simulations.

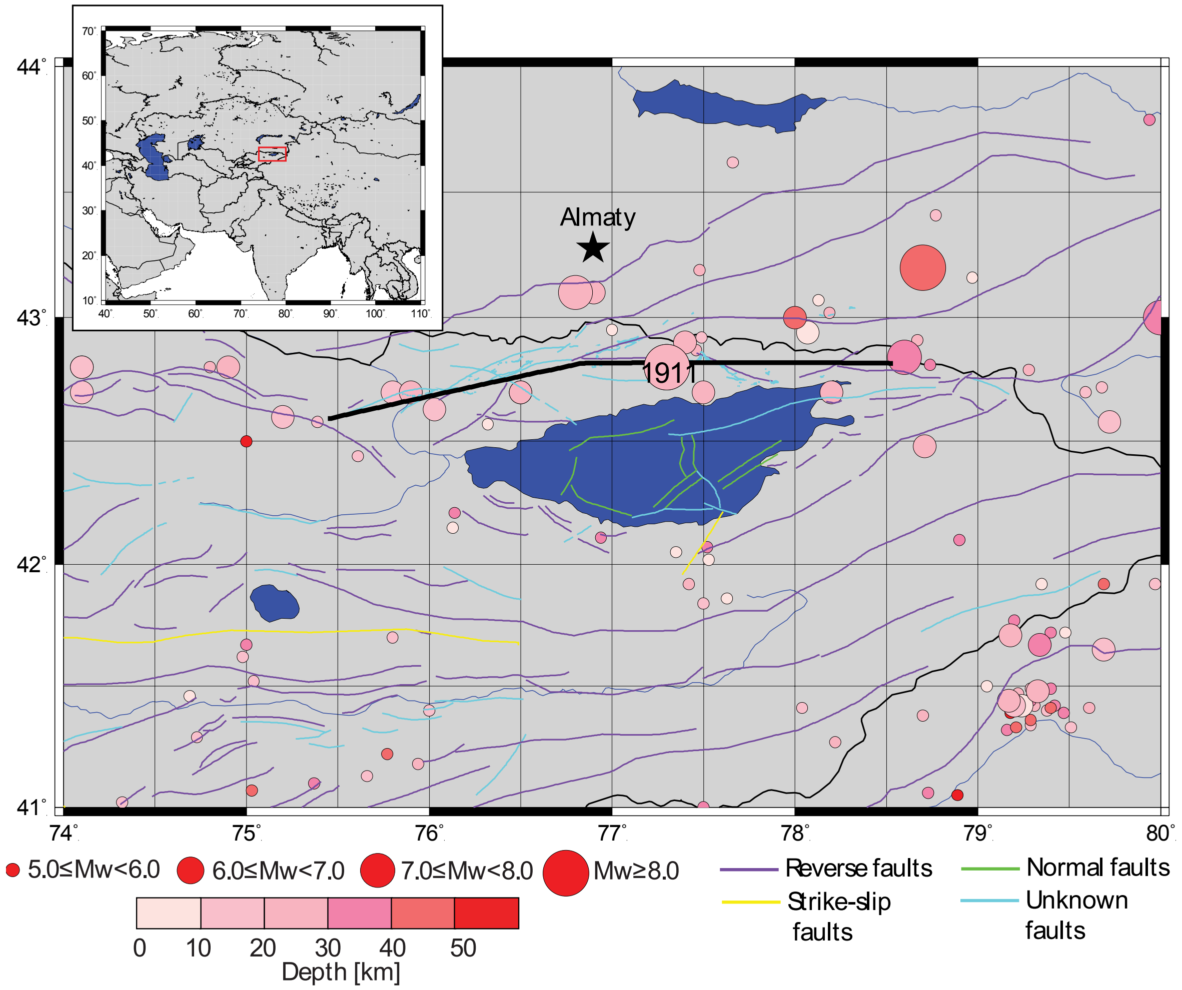
Here, we show the results for the Chon-Kemin earthquake of 3 January 1911, the strongest instrumental event recorded in Tien Shan.

Kulikova & Krüger (2015) use historic seismograms to calculate a magnitude of 8 Mw and a reverse faulting focal mechanism with a minor strike-slip component for this earthquake.

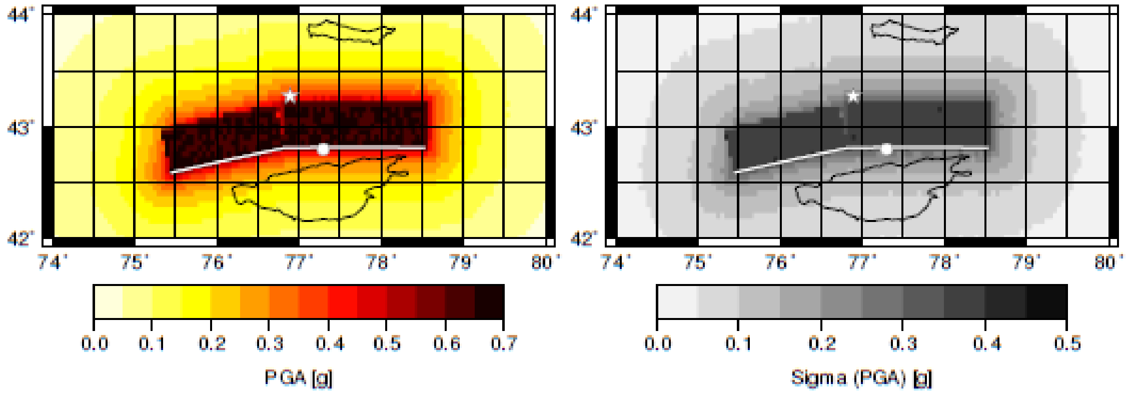
Applying the empirical relationships of Leonard (2010) we estimate that a 8 Mw earthquake generates a rupture area of 260 km length, 71 km down-dip width, a seismic moment of 3.08×10^{21} Nm and an average slip of 5 m.

There is not a specific GMPE for the Tien Shan region, so we use the GMPE of Boore & Atkinson (2008), updated in Atkinson and Boore (2011). We simulated the peak-ground-acceleration for bedrock conditions on a regular 0.05x0.05° grid covering the area between 42° and 44°N latitude and 74° and 80°E longitude for the 1911 Chon-Kemin earthquake.

The PGA value in the city of Almaty is between 0.16 and 0.63 g. Clearly, this estimate is associated with large uncertainties and the standard deviations are almost the same as the average values, due to the large uncertainty in the GMPE.



Seismo-tectonic map of the study area. The seismicity is from World Seismicity Database (Henni et al., 1998) and post-1900 seismicity is from the International Seismicity Centre database (Bondár and Storchak, 2011). The tectonic structures are from the Active Tectonics Group at Arizona State University. The fault rupture of the 1911 Chon-Kemin earthquake is indicated by the black line.



Distribution of PGA, together with the error-bar, for the 1911 Chon-Kemin earthquake. The mean and the error-bars of the ground motion fields have been computed from 5000 scenarios. The white star indicates the city of Almaty. The white line and the white dot describe the epicentre and the fault rupture, respectively.

Scientific Objectives

Local Magnitude Discrepancies for 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 examine this problem in greater detail and consider a modification to the existing magnitude scale.

Robust estimation of earthquake magnitudes is an essential part of establishing a reliable catalogue of seismic activity for seismic hazard assessments. The sizes of seismic events in the UK are routinely estimated using a local magnitude scale that is based on the maximum amplitude (often L_g) within the seismic recording (e.g. Booth, 2007). This is the same scale proposed by Richter (1935) for Southern California, defined as

$$M_L = log_{10}\left(\frac{A}{A_0}\right)$$

where A is the maximum deflection, zero to peak in millimetres registered by the earthquake on a Wood-Anderson seismograph, and A_0 is the deflection produced by a “standard” magnitude zero earthquake at the same distance. The A_0 factor allows observed amplitudes to account for decay between the seismograph and the epicentre of the earthquake. Values for A_0 were given by Richter (1935) to distances up to 600 km. A magnitude 3 earthquake was defined as a 1mm displacement at 100km.

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. Ottemoller 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)

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

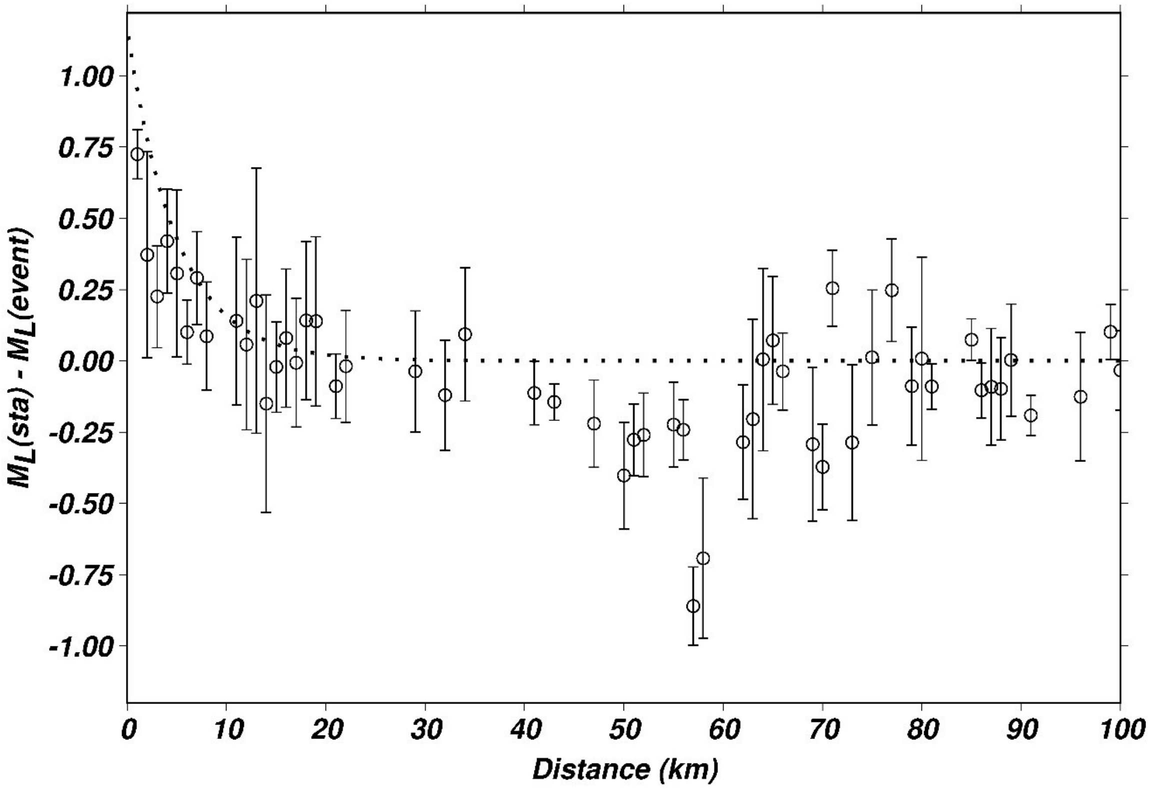
Recent research has shown that amplitude measurements from epicentral distances of less than 15-20 km considerably overestimate event magnitudes compared to more distant observations. For example, magnitudes calculated for earthquakes induced by hydraulic fracturing at Preese Hall, Lancashire (Clarke 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. In many cases this would cause a considerable increase in the event magnitude, beyond the magnitude expected from macroseismic information. As a result, such amplitudes have not been included when calculating the magnitude.

This has not been a serious problem up to now because it happens so infrequently: less than 100 examples exist from the last four decades. However, the issue has recently become of great interest because of concerns about induced seismicity.

Following the induced seismicity linked to fluid injection during hydraulic fracturing near Blackpool, UK, in 2011, the UK Department for Energy and Climate Change (DECC, 2013) published a regulatory roadmap outlining regulations for onshore oil and gas (shale gas) exploration in the UK. These regulations contain specific measures for the mitigation of induced seismicity including using a ‘traffic light’ system that controls whether injection can proceed or not, based on that seismic activity. The traffic light threshold for the cessation of hydraulic fracturing operations is currently set at 0.5 ML, where the units ML refer to the Local Magnitude scale. Such events will only be detected by sensitive monitoring equipment in the vicinity of the epicentre.

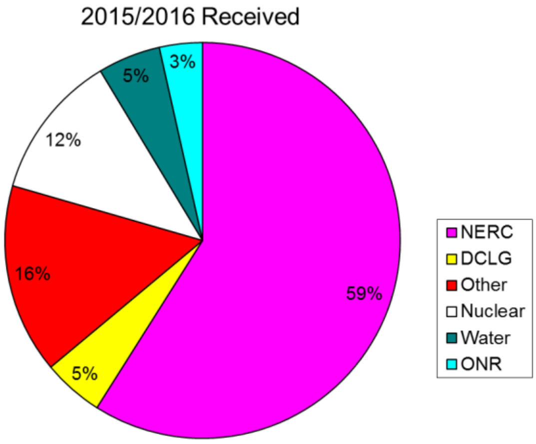
The problem discussed here has important implications for any traffic light system based on local magnitude since magnitudes calculated using observations from distances less than 10-20 km will be biased to higher magnitudes. This will result in unnecessary cessation of activities, costly shutdown procedures and possible public alarm. If these problems are to be avoided a new local magnitude scale that can be applied to observations from distances of a few kilometres to hundreds of kilometres is urgently required.

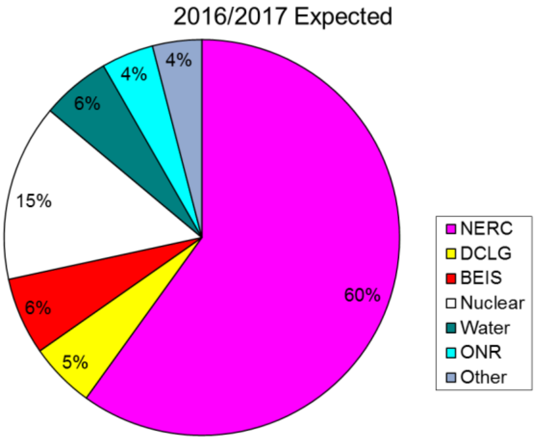


Residuals between station magnitude and event magnitude for the 92 earthquakes selected from the BGS catalogue. Each data point marks the average of all the residuals calculated at that hypocentral distance. Averages are only plotted for distances with more than three observations and the error bars show one standard deviation.

Funding and Expenditure

In 2015-2016 the project received a total of £817k including a contribution of £570k from NERC. Some of the NERC funding was won from specific funding calls. This was matched by a total contribution of £247k from the customer group drawn from industry, regulatory bodies and central and local government.





The projected income for 2016-2017 is slightly less than that received in 2015-2016, due to some aligned projects and additional funding from DECC for the UKArray project. The NERC contribution for 2016-2017 currently stands at £522k, but we hope to increase this through applications for additional funding through the year. The total expected customer group contribution for 2016-2017 currently stands at £349k. Currently, other potential sponsors are being explored.

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
Julian Bukits	Seismic analysis, preparation of data products
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

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Appendix 3: Publication Summaries

Transtensional deformation of Montserrat revealed by shear wave splitting.

Baird, A. F., Kendall, J-M., Sparks, R. S. J. and Baptie, B., 2015.

Here we investigate seismic anisotropy of the upper crust in the vicinity of Soufrière Hills volcano using shear wave splitting (SWS) analysis from volcano-tectonic (VT) events. Soufrière Hills, which is located on the island of Montserrat in the Lesser Antilles, became active in 1995 and has been erupting ever since with five major phases of extrusive activity. We use data recorded on a network of seismometers between 1996 and 2007 partially spanning three extrusive phases. Shear-wave splitting in the crust is often assumed to be controlled either by structural features, or by stress aligned cracks. In such a case the polarization of the fast shear wave (ϕ) would align parallel to the strike of the structure, or to the maximum compressive stress direction. Previous studies analyzing SWS in the region using regional earthquakes observed temporal variations in ϕ which were interpreted as being caused by stress perturbations associated with pressurization of a dyke. Our analysis, which uses much shallower sources and thus only samples the anisotropy of the upper few kilometres of the crust, shows no clear temporal variation. However, temporal effects cannot be ruled out, as large fluctuations in the rate of VT events over the course of the study period as well as changes in the seismic network configuration make it difficult to assess. Average delay times of approximately 0.2 s, similar in magnitude to those reported for much deeper slab events, suggest that the bulk of the anisotropy is in the shallow crust. We observe clear spatial variations in anisotropy which we believe are consistent with structurally controlled anisotropy resulting from a left-lateral transtensional array of faults which crosses the volcanic complex.

Assessment of existing baseline monitoring operated worldwide for UGEE projects/ operations

Baptie, B., 2015.

Recent experience in UGEE suggests that baseline monitoring should be an essential requirement of future exploration and extraction, so that background levels of seismicity can be reliably characterised and any active faults that could potentially be affected by exploration and extraction operations can be identified. Baseline monitoring is also essential for discriminating any induced earthquakes from natural background earthquake activity, allowing seismicity rates before, during and after operations to be reliably compared and any differences to be identified.

Baseline monitoring must be established prior to the commencement of any activity that is known to induce earthquakes. However, the duration of the monitoring required before operations start will depend on both the state of existing monitoring and the activity rate of the natural earthquake activity. In general, areas with higher activity rates will require shorter periods of monitoring. In areas where activity rates are low, the number of earthquakes in a given period of time may be very low, so longer durations of baseline monitoring are required to reliably determine seismicity rates. This is in keeping with experience in the geothermal industry, where monitoring periods of 6-12 months are common.

Current best estimates of the seismicity rate across Ireland and the surrounding offshore area are low, as demonstrated by the low numbers of observed earthquakes. Scaling these rates to the study areas, suggests that there would be an earthquake with a magnitude of 2 or greater roughly every 60 years in the larger of the two study areas, and even fewer earthquakes in the smaller study area. The low expected seismicity rate presents a significant challenge for this project, since it may require many decades of baseline monitoring to fully characterise the rates in each of the two study areas, if the levels of natural seismicity are as low as expected from the available historical and instrumentally recorded data. However, it is important to test the assumption that seismicity rates are uniform across Ireland. Therefore detailed monitoring will be required in each study area to detect any unusual seismicity that may suggest that seismicity rates are higher in the study areas, or that there is seismicity associated with any specific fault structure. One to two years may be an appropriate monitoring period for this purpose.

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

Reliable location and magnitude measurement places additional constraint on network design, since measurements at more stations are needed than for detection alone. In addition, location errors depend on the distribution and density of the recording stations. These errors may be large if the station density is insufficient, or if the closest stations are far from the earthquake source. Large errors are likely to limit the capability to discriminate between induced and natural earthquakes. Again, a uniform station density is required to ensure comparable location accuracy across the region of interest, with monitoring stations extending beyond the area of interest.

Extensive experience of seismic monitoring developed by the geothermal industry may be considered as “best practice” for UGEE. This will allow many of the methods used for the monitoring of earthquake activity, along with appropriate control measures for the mitigation of risks associated with induced earthquakes, to be readily adopted. The final design for the proposed baseline monitoring system will be presented in Interim Report A2.2. However, it should be noted that while seismic monitoring is used before, during and after geothermal operations, the aim of this study is solely to characterise the background natural seismicity in the study areas.

The case studies discussed in this report highlight the importance of an appropriate monitoring network for reliable detection and location of any seismic events before, during and after any operations that may induce seismic activity. In particular, the example of the seismicity induced by hydraulic fracturing at Preese Hall, near Blackpool, shows how local monitoring stations are essential to reduce uncertainty and also allay public concern.

Assessment of existing data on natural seismicity in the island of Ireland

Baptie, B., 2015.

It is well known that Ireland is a region of low seismic activity. The historical seismicity of Ireland has been studied by a number of researchers and a review of published data confirms that earthquake activity in Ireland is very low. Historical accounts of seismic events felt in Ireland amount to only 26 events in the time period 1500 to 1970, which can be deemed credible. Given the good standard of historical records in Ireland in this period, it seems quite unlikely that any significant earthquakes are yet to be discovered. Half of these accounts can be attributed to earthquakes that occurred outside Ireland in England, Scotland or Wales, where there is substantial evidence of widely felt and occasionally damaging earthquakes stretching back many hundreds of years. These were nearly all events of around magnitude 5 ML or above that occurred in the western part of Britain and were widely felt across Britain and Ireland. The other thirteen events occurred in Ireland and the immediate offshore area.

Earthquake intensity is a qualitative measure of an earthquake determined from the observed effects on people, objects and buildings. A number of intensity scales have been developed including Modified Mercalli (MM) and the European Macroseismic Scale (EMS). These consist of increasing levels of intensity, each designated by a Roman numeral, and ranging from imperceptible shaking (I) to catastrophic destruction (XII). For a given earthquake, intensity is normally greatest at the epicentre and decreases with distance from the epicentre. Intensity can be determined from historical accounts of earthquakes and used to estimate an earthquake location and magnitude. Historical earthquakes in Ireland have low intensities and were generally only felt over small areas suggesting that these were small earthquakes. Locations have been assigned to these earthquakes directly from the area of maximum felt intensity, however, magnitudes have not been determined, except for the magnitude 4.4 ML earthquake in the Irish Sea in 1951, for which instrumental data from the seismograph at Rathfarnham Castle was available. Historical earthquakes in Ireland are observed in three localities: Wicklow, Wexford and the Irish Sea on the east coast; Donegal, in the north; and the south coast of Ireland around Cork.

Instrumental data from the Dublin Institute of Advanced Studies (DIAS) and the British Geological Survey (BGS) catalogues also confirm these low rates of seismic activity. Ireland had at least one operational seismograph throughout the 20th Century and the first seismograph network was installed in 1977. Almost all the instrumental seismicity lies in areas where historical earthquakes have occurred. Mainly, Wicklow and the Irish Sea; Wexford, Waterford and Cork on the south coast of Ireland; and, Donegal in the north. The exception to this is the magnitude 4.0 ML earthquake off the coast of Mayo in 2012, which is the largest Irish event in the catalogue. Nearly all the seismic activity in Ireland, both instrumental and historical is concentrated around the coast and there is an almost complete absence of seismicity inland, with only two instrumentally recorded earthquakes in County Leitrim.

Comparison of the DIAS and BGS instrumental earthquake catalogue clearly shows that the locations and magnitudes for the common events in each are very similar, although small differences arise for those earthquakes which are a considerable distance offshore to the west of Ireland.

The combined historical and instrumental catalogue was used to determine earthquake activity rate for Ireland, i.e. the number of earthquakes above a given magnitude in a given period of time. However, the calculated rates were found to vary depending on the assumed level of completeness of the earthquake catalogue. Using the same catalogue completeness thresholds as for Britain suggests that there should be an earthquake with a magnitude of 4 MW or greater, somewhere in Ireland and the surrounding offshore area, approximately every 476 years. This is reasonable agreement with the observed data. However, using a more conservative estimate of catalogue completeness leads to a higher activity rate, which would lead to significantly more earthquakes than observed. This highlights the problem of estimating reliable rates in low seismicity regions that allow seismic hazard to be reliably quantified.

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

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

Examination of global experience of seismic events stimulated by UGEE operations

Baptie, B., 2015.

The process of hydraulic fracturing in order to increase the permeability of reservoir formations and stimulate the recovery of hydrocarbons is generally accompanied by microseismicity, commonly defined as earthquakes with magnitudes of less than 2.0 and too small to be felt. The mechanisms for this are generally well understood. Firstly, the injection of fluids under high pressure generates new cracks and fractures in a previously intact rock mass. As these grow and spread they are accompanied by brittle failure of the rock and corresponding microseismic events. In this report, these are referred to as “fracked” events. The size of these “fracked” events is constrained by the energy of the injection process. Secondly, both presence of high pressure fluid and the stress perturbation caused by the fluid can change the effective stress on pre-existing faults, causing them to fail. In this report, these events are referred to as “triggered” events. Since small stress perturbations can cause relatively large earthquakes the size of these events depends largely on the amount of stored up elastic strain energy already in the rocks.

The general consensus among most authors is that the process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing either felt, damaging or destructive earthquakes. Experience in the U.S., where many thousands of stimulations have been carried out suggest that the magnitudes of the induced earthquakes in reservoirs such as the Barnett and Marcellus Shales are typically less than 1 Mw. However, it should be pointed out that most sites of UGEE operations lack independent instrumentation for monitoring induced seismicity and that earthquakes with magnitudes of 2.5 or less will fall below the detection thresholds of regional seismic monitoring networks. Earthquakes of this size are unlikely to be felt or even detected unless local seismic monitoring networks are in place. There are only three documented examples of earthquakes with magnitudes greater than two that have be conclusively linked to hydraulic fracturing for shale gas exploration/recovery: a magnitude 2.3 ML earthquake in Blackpool, UK in 2011; from 86 earthquakes in Garvin County, South-Central Oklahoma in 2011, 16 had a magnitude of greater than 2.0 ML and the largest had a magnitude 2.9 ML; in a sequence of over 200 earthquakes in Horn River, Canada, also in 2011, 21 had magnitudes of 3 ML or greater and the largest had a magnitude of 3.8 ML. It is likely that an earthquake similar in magnitude to the largest that occurred in Horn River, Canada, would be strongly felt and could even cause some superficial damage. The maximum magnitudes observed in Blackpool and Garvin County would be unlikely to cause any damage.

By contrast, the growing body of evidence of changes in observed seismicity rates and significant earthquakes linked to long term disposal of waste water from the hydrocarbon and other industries by injection into deep sedimentary strata suggests that this activity may pose a rather greater seismic risk. Earthquakes with magnitudes comparable to the magnitude 5.7 earthquake in Prague, central Oklahoma have a non-negligible contribution to the seismic hazard in such regions and should be considered in any long term assessments of seismic hazard.

Experience of induced seismicity in Enhanced Geothermal Systems have led to a series of measures to address induced seismicity that may be considered as “industry best practice”, and, as such, may be considered appropriate for mitigating the risk of induced seismicity in UGEE operations. For example, an operational traffic light system linked to real-time monitoring of seismic activity is an essential mitigation strategy that will also need to accompany any UGEE operations in Ireland. This will require the definition of acceptable thresholds for the cessation and recommencement of operations and these should be based on levels of ground motion which may represent a hazard or a public nuisance. Existing regulatory guidelines for ground vibrations caused by blasting could also provide a useful framework for this purpose. The direct use of ground motion thresholds rather than derived magnitudes may, in some case, be preferable as those allows thresholds to be directly related to these regulatory guidelines. Other means of mitigating earthquake risk may require improved understanding of the Earth’s sub-surface in areas of unconventional hydrocarbon potential, such as better characterisation of existing fault zones, which may be difficult to achieve without detailed geophysical surveying.

Controlling factors on seismicity induced by hydraulic fracturing include: the strength of rocks in the geological formations of interest; the size and state of stress of any faults in the area likely to be affected by fluid injection; and, the pressure change induced by the hydraulic fracture process. The pre-existing state of stress on a fault determines how close it is to failure, so faults that are critically stressed may require only a small stress perturbation to cause them to fail. The pressure change induced by the hydraulic fracture process is mainly controlled by the volume of injected fluid and the rate of injection, where larger volumes and higher injection rates generate higher pressures. Recent work suggests that maximum magnitude is related to the total volume of injected fluid.

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

Finally, it should be noted that seismological methods alone cannot discriminate between man-made and natural tectonic earthquakes. This strengthens the case for site specific seismic monitoring and detailed recording of injection parameters, to reduce uncertainties in earthquake locations and to compare the temporal evolution of seismic activity with any hydraulic fracture operations.

Technical Memorandum NGS_15 (commercial in confidence)

Baptie, B., 2015.

A technical memorandum for the Draft Detailed Technical Instruction (Natural Processes, Earthquakes) produced as part of the national geological screening process for the possible siting of a Geological Disposal Facility (GDF).

Technical Memorandum NGS_20 (commercial in confidence)

Baptie, B., 2015.

A technical memorandum for the Draft Detailed Technical Instruction (Natural Processes, Earthquakes) produced as part of the national geological screening process for the possible siting of a Geological Disposal Facility (GDF).

Constructing new seismograms from old earthquakes: retrospective seismology at multiple length scales.

Entwistle, E., Curtis, A., Galetti, E., Baptie, B. and Meles, G., 2015.

If energy emitted by a seismic source such as an earthquake is recorded on a suitable backbone array of seismometers, source-receiver interferometry (SRI) is a method that allows those recordings to be projected to the location of another target seismometer, providing an estimate of the seismogram that would have been recorded at that location. Since the other seismometer may not have been deployed at the time at which the source occurred, this renders possible the concept of “retrospective seismology” whereby the installation of a sensor at one period of time allows the construction of virtual seismograms as though that sensor had been active before or after its period of installation. Here we construct such virtual seismograms on target sensors in both industrial seismic and earthquake seismology settings, using both active seismic sources and ambient seismic noise to construct SRI propagators, and on length scales ranging over 5 orders of magnitude from ∼40 m to ∼2500 km. In each case we compare seismograms constructed at target sensors by SRI to those actually recorded on the same sensors. We show that spatial integrations required by interferometric theory can be calculated over irregular receiver arrays by embedding these arrays within 2-D spatial Voronoi cells, thus improving spatial interpolation and interferometric results. The results of SRI are significantly improved by restricting the backbone receiver array to include approximately those receivers that provide a stationary-phase contribution to the interferometric integrals. Finally, we apply both correlation-correlation and correlation-convolution SRI and show that the latter constructs fewer nonphysical arrivals.

Uncertainty Loops in Travel-Time Tomography from Nonlinear Wave Physics.

Galetti, E., Curtis, A., Meles, G. and Baptie, B., 2015.

Estimating image uncertainty is fundamental to guiding the interpretation of geoscientific tomographic maps.We reveal novel uncertainty topologies (loops) which indicate that while the speeds of both low- and high-velocity anomalies may be well constrained, their locations tend to remain uncertain. The effect is widespread: loops dominate around a third of United Kingdom Love wave tomographic uncertainties, changing the nature of interpretation of the observed anomalies. Loops exist due to 2nd and higher order aspects of wave physics; hence, although such structures must exist in many tomographic studies in the physical sciences and medicine, they are unobservable using standard linearized methods. Higher order methods might fruitfully be adopted.

Local earthquake tomography of Scotland

Luckett, R. and Baptie, B., 2015

Scotland is a relatively aseismic region for the use of local earthquake tomography, but 40 yr of earthquakes recorded by a good and growing network make it possible. A careful selection is made from the earthquakes located by the British Geological Survey (BGS) over the last four decades to provide a data set maximising arrival time accuracy and ray path coverage of Scotland. A large number of 1-D velocity models with different layer geometries are considered and differentiated by employing quarry blasts as ground-truth events. Then, SIMULPS14 is used to produce a robust 3-D tomographic P-wave velocity model for Scotland. In areas of high resolution the model shows good agreement with previously published interpretations of seismic refraction and reflection experiments. However, the model shows relatively little lateral variation in seismic velocity except at shallow depths, where sedimentary basins such as the Midland Valley are apparent. At greater depths, higher velocities in the northwest parts of the model suggest that the thickness of crust increases towards the south and east. This observation is also in agreement with previous studies. Quarry blasts used as ground truth events and relocated with the preferred 3-D model are shown to be markedly more accurate than when located with the existing BGS 1-D velocity model.

Benchmarking Recent PSHA Approaches.

Mosca, I., Sargeant, S. and Musson, R.M.W., 2015.

Seismic hazard assessment (SHA), or analysis, plays a crucial role in building design and informing decision making for the mitigation of seismic risk. In the last decades a large number of studies in probabilistic seismic hazard assessment have been published where different criteria have been used for characterizing the source zone model, for selecting the most suitable ground motion models in the study area, for computing hazard itself, etc. Therefore, it is important to check whether the output of a seismic hazard study is compatible with the input, and to compare approaches and software packages used in SHA. The aim of the present study is to analyse three approaches for probabilistic seismic hazard assessment and their associated software packages: OpenQuake, the most recent software for seismic hazard and risk assessment (Crowley et al, 2013; Pagani at al., 2014); M3C (Musson, 1999; Musson et al., 2009) and EqHaz (Assatourians & Atkinson, 2013), based both on Monte Carlo simulations to calculate the hazard. The comparison is made in terms of methodology, computer performance of the software packages and hazard results, including hazard curves and maps. The main conclusion from the present work is that if the input parameters are identical, the outputs from any type of approach for seismic hazard analysis have an excellent agreement. Results computed from M3C and OpenQuake are very similar to each other; whereas, the discrepancies between EqHaz and the other two software packages are explained by inherent features of the code EqHaz.

An assessment of seismic hazard for Tristan da Cunha.

Mosca, I, Sargeant, S. and Baptie, B., 2015.

This report is the published product of a seismic hazard assessment for Tristan da Cunha for the Department for International Development by the British Geological Survey (BGS). The project consists of two phases. The first (Phase 1) considers the earthquake hazard resulting from volcanic activity associated with the Tristan da Cunha volcano. The second (Phase 2) considers the hazard associated with large (M~7.5) earthquakes in the South Atlantic. This report contains the results from both phases of the project.

What Was The Largest British Earthquake?

Musson, R., 2015.

The issue of “largest observed earthquake in a region” is both important for seismic hazard analysis and also of journalistic and popular interest. Identifying the relevant event is not always straightforward in intraplate regions such as the UK, where the historical earthquake catalogue is short with respect to the seismic cycle. In Britain, the largest 20th century event (i.e. instrumentally recorded) was the North Sea earthquake of 7 June 1931. However, there are several pre-instrumental earthquakes that affected Britain which may have been as large or larger. However, the task of estimating magnitude from often very scant historical accounts is difficult, and leads to much speculation. In this paper, the evidence for four such earthquakes is reviewed, but it is not possible to come to a firm conclusion regarding any of them.

Water, oceanic fracture zones and the lubrication of subducting plate boundaries : insights from seismicity

Schlaphorst, D., Kendall, J.-M., Collier, J. S., Verdon, J. P., Blundy, J., Baptie, B., Latchman, J. L., Massin, F., Bouin, M.-P., 2016.

We investigate the relationship between subduction processes and related seismicity for the Lesser Antilles Arc using the Gutenberg–Richter law. This power law describes the earthquake-magnitude distribution, with the gradient of the cumulative magnitude distribution being commonly known as the b-value. The Lesser Antilles Arc was chosen because of its along-strike variability in sediment subduction and the transition from subduction to strike-slip movement towards its northern and southern ends. The data are derived from the seismicity catalogues from the Seismic Research Centre of The University of the West Indies and the Observatoires Volcanologiques et Sismologiques of the Institut de Physique du Globe de Paris and consist of subcrustal events primarily from the slab interface. The b-value is found using a Kolmogorov–Smirnov test for a maximum-likelihood straight line-fitting routine. We investigate spatial variations in b-values using a grid-search with circular cells as well as an along-arc projection. Tests with different algorithms and the two independent earthquake cataloges provide confidence in the robustness of our results. We observe a strong spatial variability of the b-value that cannot be explained by the uncertainties. Rather than obtaining a simple north–south b-value distribution suggestive of the dominant control on earthquake triggering being water released from the sedimentary cover on the incoming American Plates, or a b-value distribution that correlates with on the obliquity of subduction, we obtain a series of discrete, high b-value ‘bull's-eyes’ along strike. These bull's-eyes, which indicate stress release through a higher fraction of small earthquakes, coincide with the locations of known incoming oceanic fracture zones on the American Plates. We interpret the results in terms of water being delivered to the Lesser Antilles subduction zone in the vicinity of fracture zones providing lubrication and thus changing the character of the related seismicity. Our results suggest serpentinization around mid-ocean ridge transform faults, which go on to become fracture zones on the incoming plate, plays a significant role in the delivery of water into the mantle at subduction zones.

Vertical Motions at the Edges of the Icelandic Plume

Schooman, C., White, N. and Luckett, R., 2015.

The Icelandic mantle plume, a major convective upwelling, has had a profound effect on the evolution of the North Atlantic region over the last 62 Myrs. Recent body and surface wave tomographic studies show that the planform of the Icelandic Plume is not circular but highly irregular, with fingers of anomalously slow mantle extending beneath the lithosphere of the British Isles and Norway. In these regions, analysis of receiver functions indicates that crustal isostasy does not completely account for present-day topographic elevation, which suggests the presence of a significant component of dynamic support. This study investigates the crustal and mantle structure above these asthenospheric fingers in order to develop an understanding of the interaction between convective processes and their topographic expression at the surface. Large teleseismic earthquakes recorded on a network of broadband, three component seismometers deployed throughout the British Isles are being used to construct receiver functions. Through forward and inverse modelling of these receiver functions, as well as joint inversion of the receiver functions and Rayleigh wave group dispersion data, the velocity structure of the crust and mantle underneath each station is determined. Preliminary results show that anomalously thin crust occurs beneath Northwest Scotland, directly above an asthenospheric finger. Further work will attempt to image the top of the anomalously hot asthenospheric finger and to extend the project into other parts of the North Atlantic Ocean, constraining the spatial distribution of any dynamic topography.

Physics-based and statistical earthquake forecasting in a continental rift zone: The case study of Corinth Gulf (Greece)

Segou, M., 2016.

I perform a retrospective forecast experiment in the most rapid extensive continental rift worldwide, the western Corinth Gulf (wCG, Greece), aiming to predict shallow seismicity (depth <15 km) with magnitude M ≥ 3.0 for the time period between 1995 and 2013. I compare two short-term earthquake clustering models, based on epidemic-type aftershock sequence (ETAS) statistics, four physics-based (CRS) models, combining static stress change estimations and the rate-and-state laboratory law and one hybrid model. For the latter models, I incorporate the stress changes imparted from 31 earthquakes with magnitude M ≥ 4.5 at the extended area of wCG. Special attention is given on the 3-D representation of active faults, acting as potential receiver planes for the estimation of static stress changes. I use reference seismicity between 1990 and 1995, corresponding to the learning phase of physics-based models, and I evaluate the forecasts for six months following the 1995 M = 6.4 Aigio earthquake using log-likelihood performance metrics. For the ETAS realizations, I use seismic events with magnitude M ≥ 2.5 within daily update intervals to enhance their predictive power. For assessing the role of background seismicity, I implement a stochastic reconstruction (aka declustering) aiming to answer whether M > 4.5 earthquakes correspond to spontaneous events and identify, if possible, different triggering characteristics between aftershock sequences and swarm-type seismicity periods. I find that: (1) ETAS models outperform CRS models in most time intervals achieving very low rejection ratio RN = 6 per cent, when I test their efficiency to forecast the total number of events inside the study area, (2) the best rejection ratio for CRS models reaches RN = 17 per cent, when I use varying target depths and receiver plane geometry, (3) 75 per cent of the 1995 Aigio aftershocks that occurred within the first month can be explained by static stress changes, (4) highly variable performance on behalf of both statistical and physical models is suggested by large confidence intervals of information gain per earthquake and (5) generic ETAS models can adequately predict the temporal evolution of seismicity during swarms. Furthermore, stochastic reconstruction of seismicity makes possible the identification of different triggering processes between specific seismic crises (2001, 2003–04, 2006–07) and the 1995 aftershock sequence. I find that: (1) seismic events with M ≥ 5.0 are not a part of a preceding earthquake cascade, since they are characterized by high probability being a background event (average Pback > 0.8) and (2) triggered seismicity within swarms is characterized by lower event productivity when compared with the corresponding value during aftershock sequences. I conclude that physics-based models contribute on the determination of the ‘new-normal’ seismicity rate at longer time intervals and that their joint implementation with statistical models is beneficial for future operational forecast systems.

Site selection strategy for environmental monitoring in connection with shale-gas exploration: Vale of Pickering, Yorkshire and Fylde, Lancashire.

Smedley, P L, Ward, R S, Allen, G, Baptie, B, Daraktchieva, Z, Jones, D G, Jordan, C J, Purvis, R M and Cigna, F., 2015.

This report outlines the strategies for site selection adopted as part of a baseline environmental monitoring investigation in connection with shale-gas exploration and development in the Vale of Pickering, North Yorkshire. The project forms an extension to an ongoing baseline investigation being carried out in the Fylde, Lancashire, and the current project incorporates an air-quality monitoring component that was not within the original remit of the Fylde study. The DECC-funded investigation is led by the British Geological Survey, and is being carried out as a collaboration with the Universities of Birmingham, Bristol, Liverpool, Manchester and York (National Centre for Atmospheric Science, NCAS) and Public Health England (PHE). The project incorporates work packages in monitoring of water quality, air quality and greenhouse gases, soil gas, ground motion and seismicity, and air radon and is being carried out over the period September 2015 to March 2016.

Site selection is a critical consideration in setting up a monitoring programme as chosen sites need to be representative of conditions to be tested. While sites will necessarily be subject to practical constraints (land access agreements, existing infrastructure, geological conditions, cost implications etc), site selection has a large part to play in ensuring collection of quantifiable, unbiased data. This report sets out the rationale for site selection in each of the work packages and the steps taken to ensure defensible site-selection decisions and to minimise the impact of practical constraints.

Interdependence and dynamics of essential services in an extensive risk context: a case study in Montserrat, West Indies

Sword-Daniels, V.L.; Rossetto, T.; Wilson, T.M.; Sargeant, S., 2015.

The essential services that support urban living are complex and interdependent, and their disruption in disasters directly affects society. Yet there are few empirical studies to inform our understanding of the vulnerabilities and resilience of complex infrastructure systems in disasters. This research takes a systems thinking approach to explore the dynamic behaviour of a network of essential services, in the presence and absence of volcanic ashfall hazards in Montserrat, West Indies. Adopting a case study methodology and qualitative methods to gather empirical data, we centre the study on the healthcare system and its interconnected network of essential services. We identify different types of relationship between sectors and develop a new interdependence classification system for analysis. Relationships are further categorised by hazard conditions, for use in extensive risk contexts. During heightened volcanic activity, relationships between systems transform in both number and type: connections increase across the network by 41%, and adapt to increase cooperation and information sharing. Interconnections add capacities to the network, increasing the resilience of prioritised sectors. This in-depth and context-specific approach provides a new methodology for studying the dynamics of infrastructure interdependence in an extensive risk context, and can be adapted for use in other hazard contexts.

Environmental Baseline Monitoring Project: Progress Report 2

Ward, R S., 2016.

This report (Progress Report 2) is submitted in compliance with the conditions set out in the grant awarded to the Natural Environment Research Council (NERC) on behalf of the British Geological Survey (BGS). It provides the information and evidence required for approval of payment of the first instalment of the grant as specified in the Schedule to Annex 2 of the Grant Agreement. The grant has been awarded to provide financial support to the project "Science-based environmental baseline monitoring associated with shale gas development in the Vale of Pickering, North Yorkshire (including supplementary air quality monitoring in Lancashire)".

Bedrock and superficial geological models have been produced and these are reported in two published reports downloadable from the website. This information has been used to identify the preferred locations for both the shallow and deep boreholes to be drilled for groundwater monitoring. The borehole drilling and their subsequent testing (including geophysical logging) will provide additional geological and hydrogeological data, and this will be used to refine both the bedrock and superficial geological models and the hydrogeological conceptual model.

Currently 24 sites are being sampled for groundwater and 10 sites for surface water. The proposal had originally specified a quarterly sampling frequency but due to the delayed start it was decided to increase this to monthly. Four sampling rounds have now been completed.

A number of problems, reported in the first progress report, delayed the installation and commissioning of the atmospheric monitoring stations. These problems have now been overcome and the Lancashire site is fully-operational with a live data being streamed over the internet. A further delay at the Kirby Misperton (Vale of Pickering) site has meant that the instrumentation will now be installed in January 2016 with live data being streamed over the internet by the end of the month. The delay was caused by Third Energy imposing restrictions on access to the site whilst they carried out operations and also in relation to reasonable objections to the site installation design.

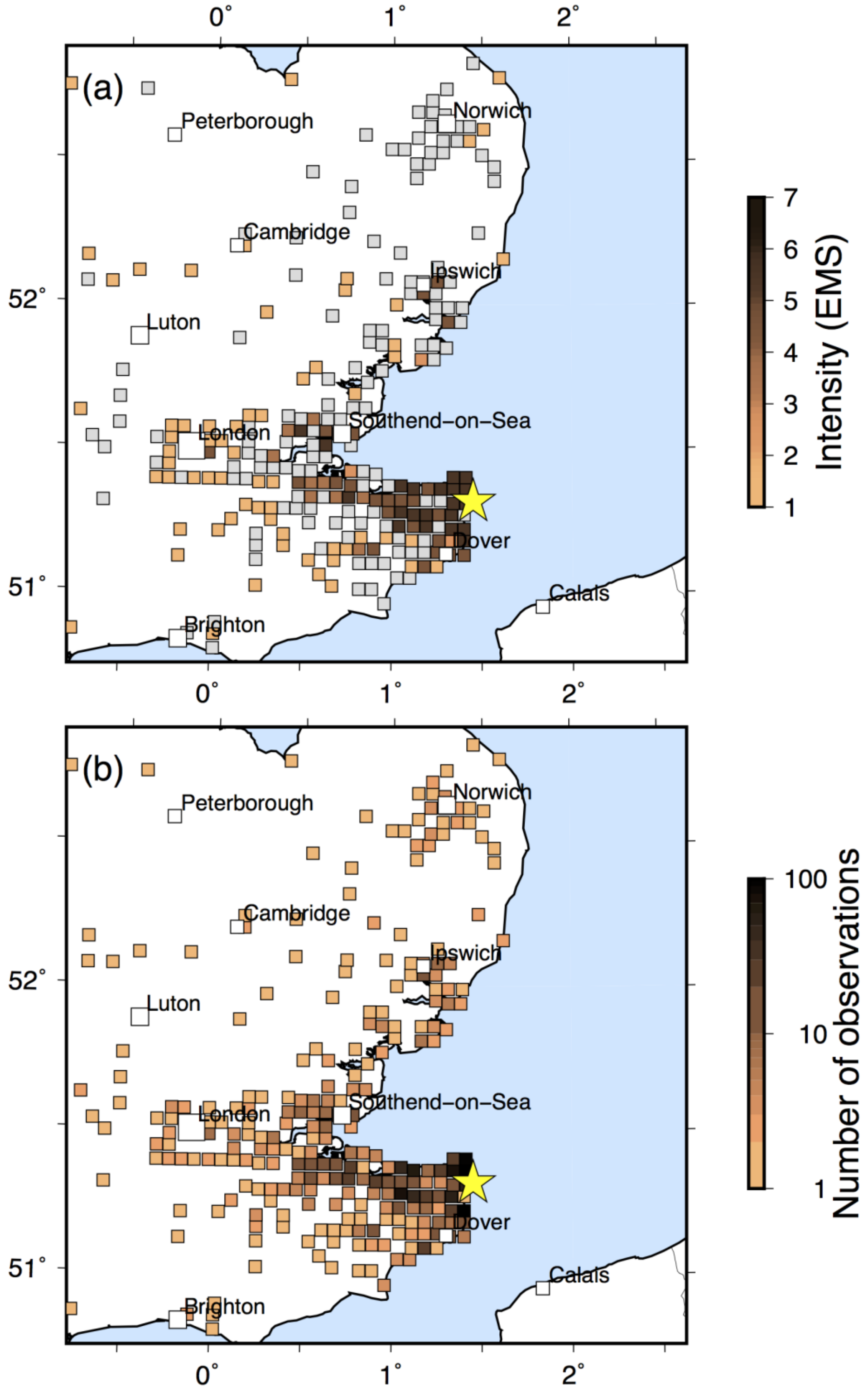
As reported in the first progress report, five surface seismometers had been installed and were streaming live data. This is continuing and is reported here. Deployment of the other seismometers (downhole) will be completed by the end of January once the shallow boreholes have been completed. The installation of the downhole seismometers will increase the detection capability of the seismic monitoring array as interference from background surface noise will be significantly reduced.

Analysis of ENVISAT radar data for the period 2002-2009 has now been completed to establish the rate of ground motion across the Vale of Pickering and surrounding areas over this period. Both urban and rural areas have been covered by SBAS and ISBAS InSAR analysis at over 300,000 points to determine ground motion velocities. Initial calculations indicate that they range from -7.35 mm/year (subsidence) to +9.32 mm/year (uplift) over this time period. Analysis for the period 1992-2000 is on-going and will be completed by the end of January 2016.

The 2013 European Seismic Hazard Model: key components and results.

Woessner, J., Laurentiu, D., Giardini, D. et al., 2015.

The 2013 European Seismic Hazard Model (ESHM13) results from a community-based probabilistic seismic hazard assessment supported by the EU-FP7 project “Seismic Hazard Harmonization in Europe” (SHARE, 2009–2013). The ESHM13 is a consistent seismic hazard model for Europe and Turkey which overcomes the limitation of national borders and includes a through quantification of the uncertainties. It is the first completed regional effort contributing to the “Global Earthquake Model” initiative. It might serve as a reference model for various applications, from earthquake preparedness to earthquake risk mitigation strategies, including the update of the European seismic regulations for building design (Eurocode 8), and thus it is useful for future safety assessment and improvement of private and public buildings. Although its results constitute a reference for Europe, they do not replace the existing national design regulations that are in place for seismic design and construction of buildings. The ESHM13 represents a significant improvement compared to previous efforts as it is based on (1) the compilation of updated and harmonised versions of the databases required for probabilistic seismic hazard assessment, (2) the adoption of standard procedures and robust methods, especially for expert elicitation and consensus building among hundreds of European experts, (3) the multi-disciplinary input from all branches of earthquake science and engineering, (4) the direct involvement of the CEN/TC250/SC8 committee in defining output specifications relevant for Eurocode 8 and (5) the accounting for epistemic uncertainties of model components and hazard results. Furthermore, enormous effort was devoted to transparently document and ensure open availability of all data, results and methods through the European Facility for Earthquake Hazard and Risk



(a) Macroseismic intensities calculated for the magnitude 4.2 ML Ramsgate earthquake on 22nd May 2015. Intensities are calculated from observations in 5 km grid squares. A minimum of five observations are required to calculate an intensity. Grey squares show places where the earthquake was felt but there were fewer than five observations. (b) Number of observations.