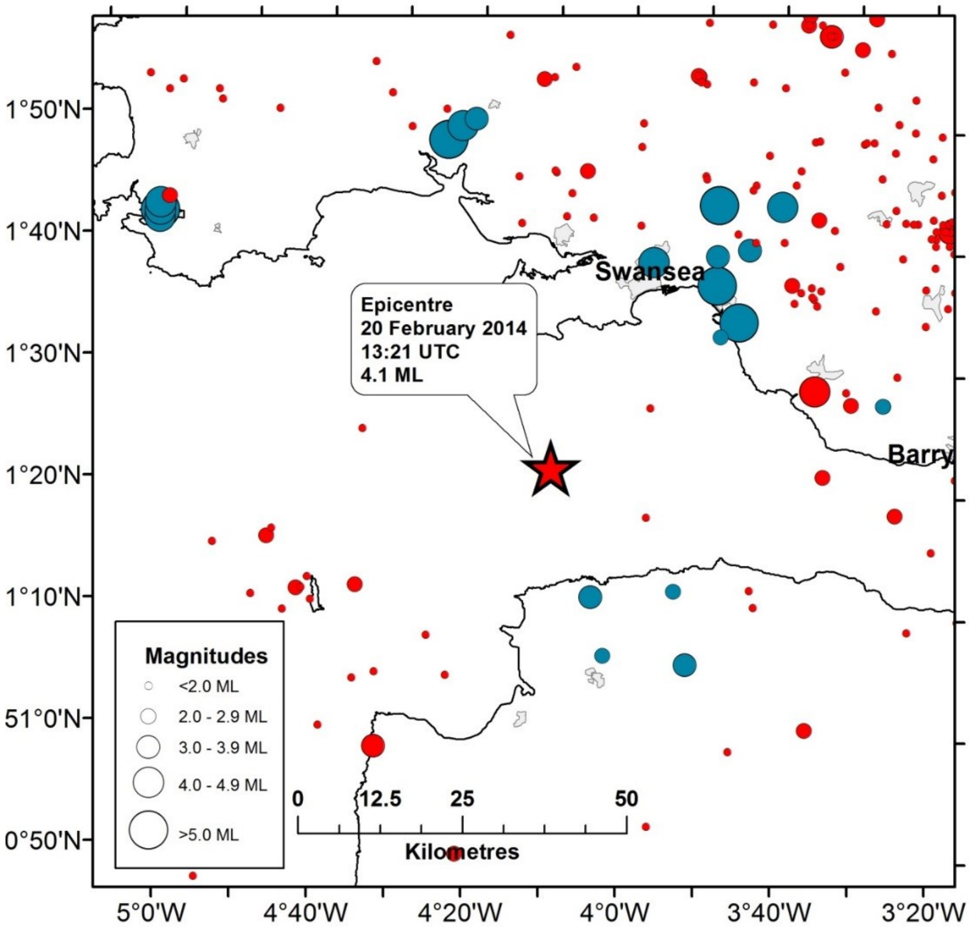
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Earthquake Monitoring 2013/2014

BGS Seismic Monitoring and Information Service

Twenty-fifth Annual Report



BRITISH GEOLOGICAL SURVEY

OPEN REPORT OR/17/065

UK Earthquake Monitoring 2013/2014

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Instrumental (red) and historical (blue) seismicity in the Bristol Channel area.

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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 24th year of the project, two new broadband seismograph stations were established, giving a total of 42 broadband stations. 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). Monthly seismic bulletins were issued six weeks in arrears and compiled in a finalised annual bulletin (Galloway, 2014).

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

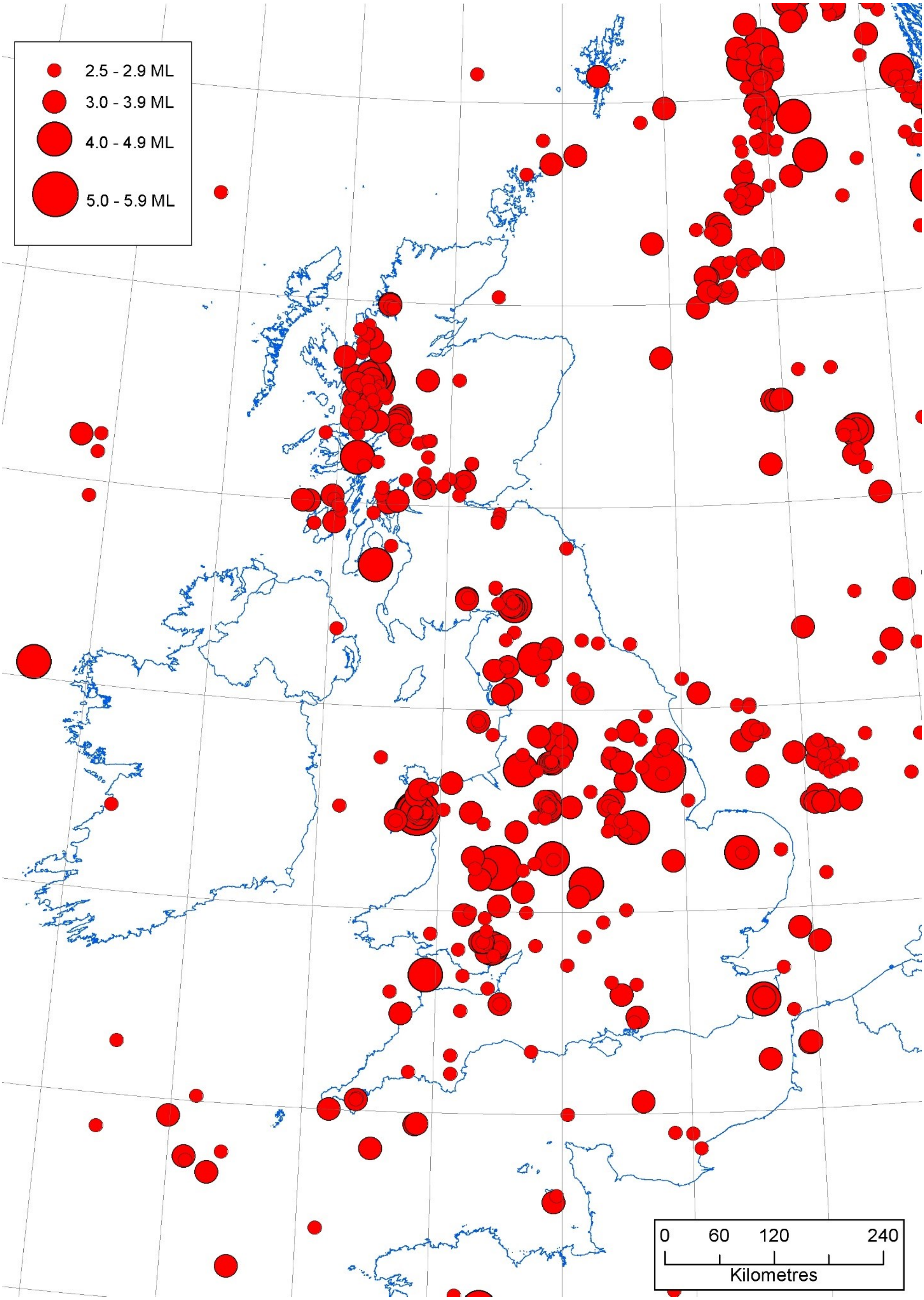
Introduction

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

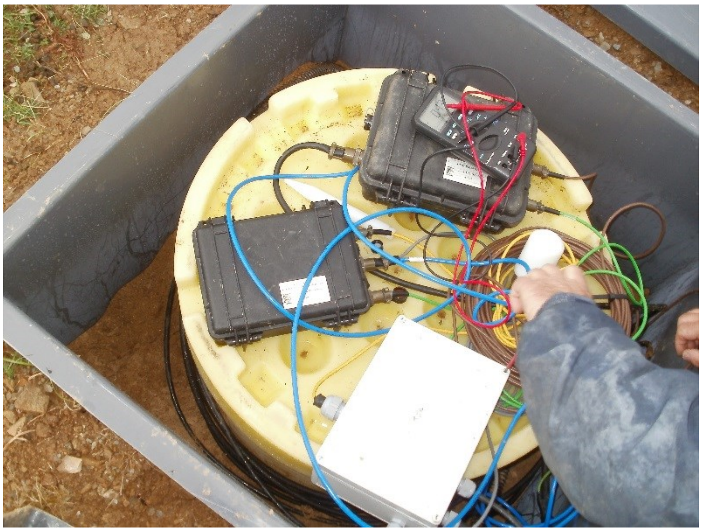
Almost every week, seismic events are reported to be felt somewhere in the UK. A small number of these prove to be sonic booms or are spurious, but a large proportion are natural or mining-induced earthquakes often felt at intensities which cause concern and, occasionally, some damage. The Information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

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

Long term earthquake monitoring is required to refine our understanding of the level of seismic hazard in the UK. Although seismic hazard and risk are low by world standards they are by no means negligible, particularly with respect to potentially hazardous installations and sensitive structures. The monitoring results help 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 2014.



Introduction

Monitoring Network

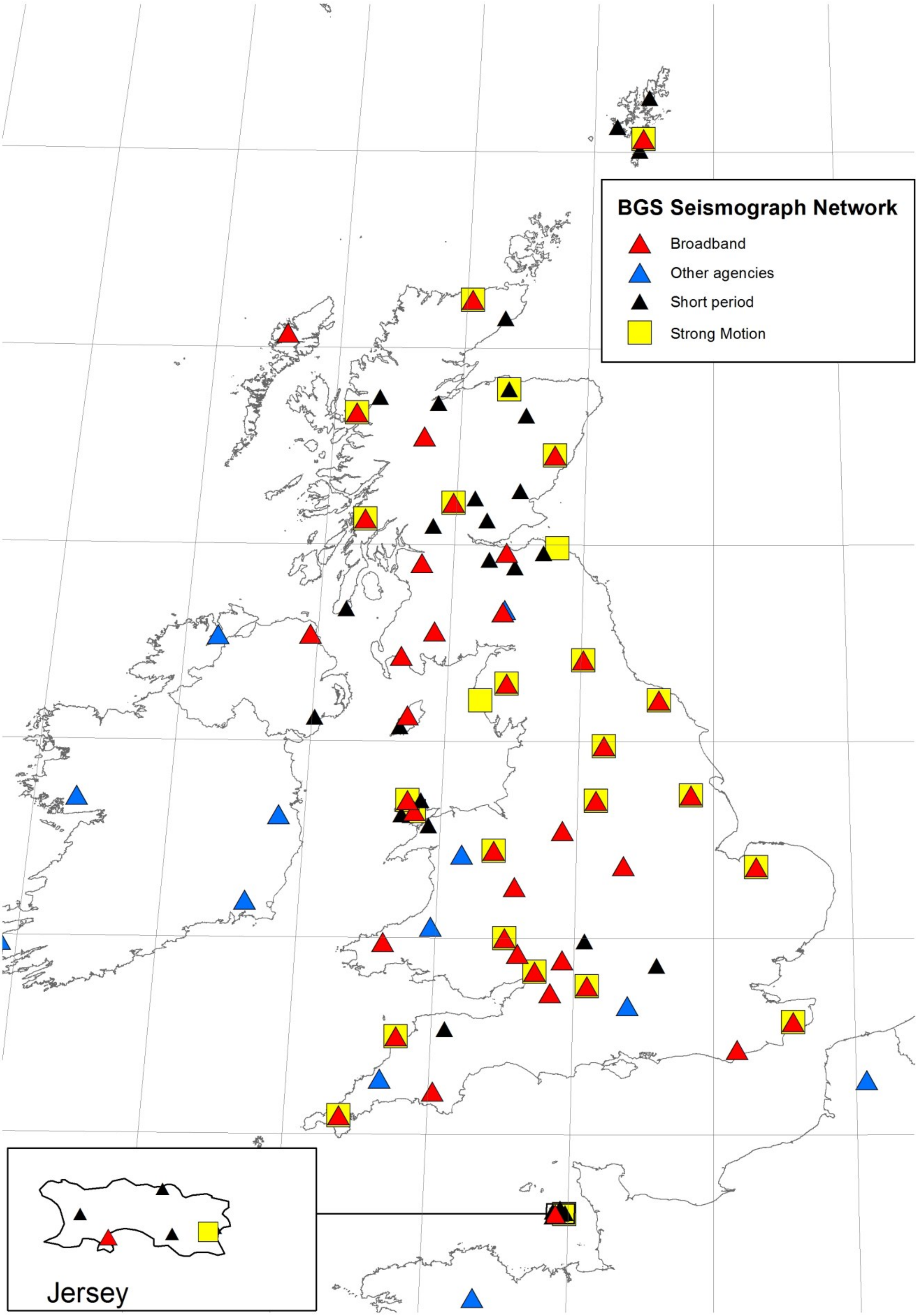
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late 1990s, the number of stations reached its peak of 146, with an average spacing of 70 km. We are now in the process 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 42 broadband sensors at stations across the UK along with 28 strong motion accelerometers with high dynamic range recording for recording very large signals.



BGS seismograph stations, March 2014

Achievements

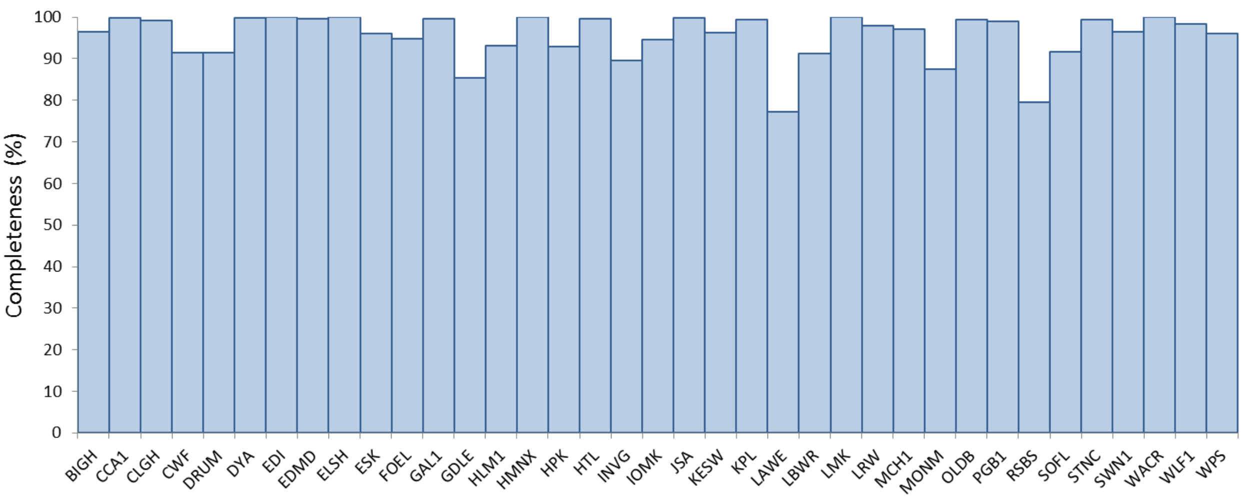
Network Development

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, two new broadband stations were installed on Lewis (Outer Hebrides) and in New Galloway (Dumfries and Galloway). This takes the total number of broadband stations operated by BGS to 42. Continuous data from all broadband stations are transmitted in real-time to Edinburgh, where they are used for analysis and archived.

Short period stations in the Minch sub-network in northwest Scotland were decommissioned in the last year. This leaves 33 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.

In addition, construction has started for a new station in Assynt and site surveys were carried out for new broadband stations in Suffolk and Sussex. It was particularly hard to identify suitable sites in both Suffolk and Sussex because of high levels of cultural noise and several surveys were required to compare various sites. We hope to install



Data completeness for all broadband stations that operated throughout 2013-2014. Data are more than 90% complete for more than 85% of stations and more than 95% complete for over 60% of stations. Stations installed during the year are not included.

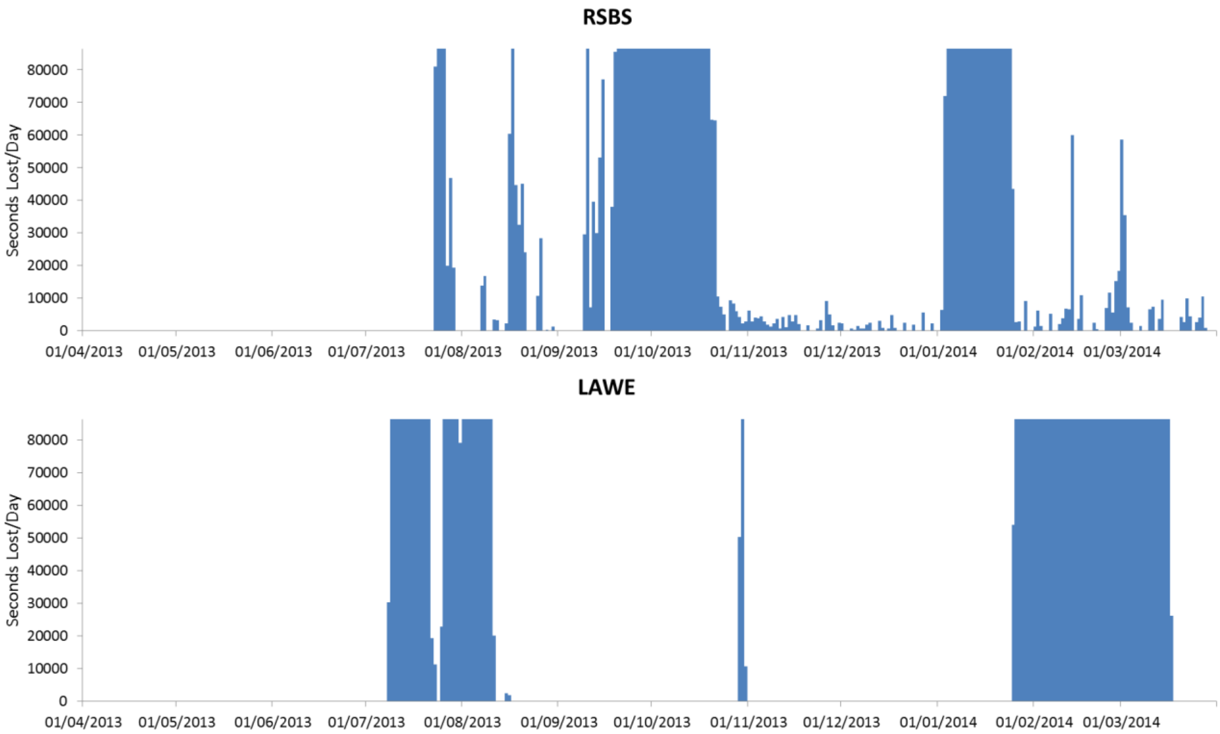
permanent stations in these areas in 2014/2015.

A planned borehole sensor in northwest England is on hold until 2015, while a capital funding bid for a borehole sensor in southeast England unfortunately failed.

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, four were to carry out site surveys for new stations, six were for installation of new stations and two were for decommissioning of old stations.

Continuous data from all our broadband and most of our short period stations are now archived at BGS. The completeness of these data can be easily checked to gain an accurate picture of network performance. For 2013-2014, data are more than 90% complete for more than 85% of stations and more than 95% complete for over 60% of stations, both of which are significant improvements over 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. Only two stations, Loch Awe (Argyll) and Rosebush (Pembroke) returned less than 80% data. In each case, considerable downtime resulted from equipment failure due to lightning strikes that were 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, e.g. the Irish Sea.



Data lost (numbers of seconds/day) for stations, Loch Awe (Argyll) and Rosebush (Pembroke) which returned 79% and 77%, respectively.

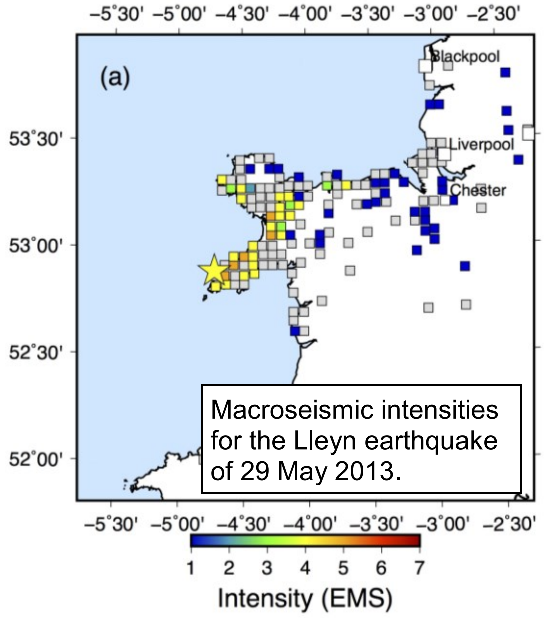
Achievements

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 37 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, three enquiries were received from Nuclear Power Stations after alarms triggered. In each case, a response was given within 15 minutes.

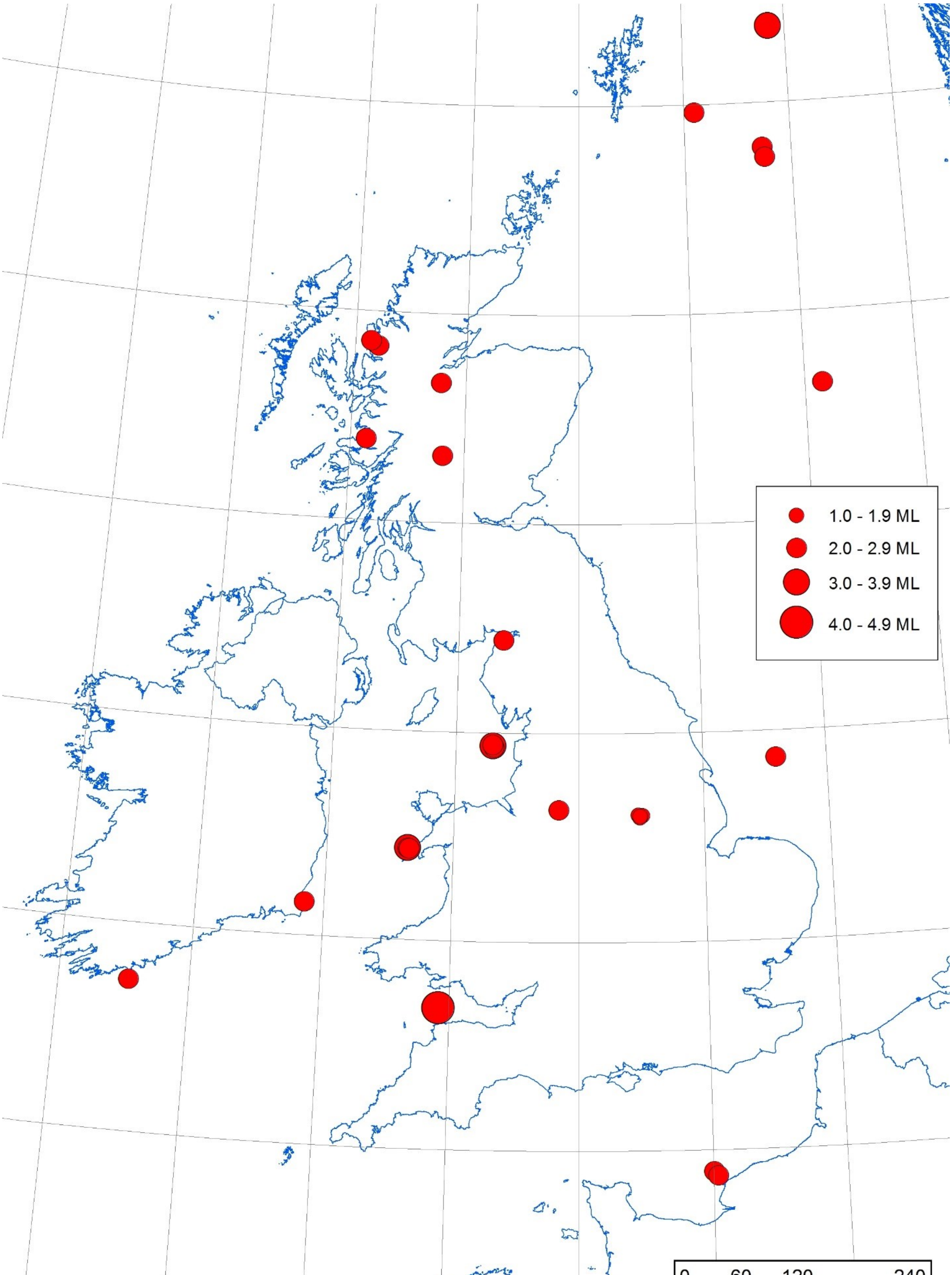
We continue to update the Seismology web pages. These web pages are directly linked to our earthquake database to provide near real-time lists of significant earthquake activity, together with automatically generated pages for each event. This greatly simplifies the task of providing earthquake information 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 300 replies following the Bristol Channel earthquake on 20 February 2014 (4.1 ML) and 514 replies following the Lleyn Peninsula Earthquake 29 May 2013 (3.8 ML).



Macroseismic intensities for the Lleyn earthquake of 29 May 2013.

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 is also defined as intensity 1). These data are processed automatically to produce the macroseismic maps for the seismology web pages.

Preliminary monthly bulletins of seismic information were produced and distributed to the Customer Group within six weeks of the end of each month. The project aim is to publish the revised annual Bulletin of British Earthquakes within six months of the end of a calendar year.



Events in the reporting period (1 April 2013 – 31 March 2014) for which alerts have been issued. Circles are scaled by magnitude. Nine of the alerts are outside the map extent.

Achievements

Collaboration and Data Exchange

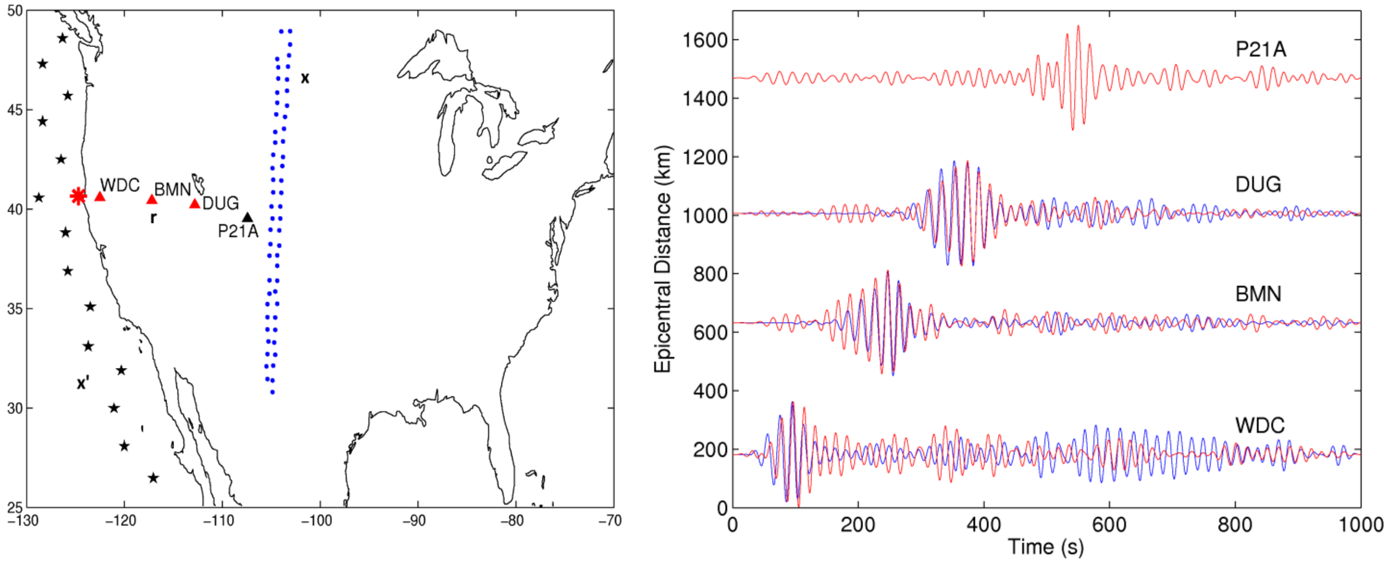
Data from the seismograph network are freely available for academic use and we have continued to collaborate with researchers at academic institutes within the UK throughout the past year, as well as exchanging data with European and world agencies.

A student at Edinburgh University, funded partly by BGS is applying source-receiver interferometry to reconstruct earthquake signals on seismometers that were not deployed until after the earthquakes occurred.

Inter-receiver Green's functions (EGFs) are estimated by cross-correlating year long records of background noise between pairs of seismometers. These EGFs are cross-correlated with real recordings of the earthquakes to reconstruct a new recording at a new location.

Examples of this include the reconstruction of the recordings of a magnitude 6.5 earthquake on the west coast of the United States using data from the USArray seismic network. Seismograms were constructed for four stations at different distances from the earthquake. These show good agreement with the real ground motions recorded at these stations after the earthquake.

A BGS CASE PhD student at the University of Cambridge is in her second year, investigating the crustal and mantle structure above areas of anomalously slow mantle beneath the British Isles using forward and inverse modelling of receiver functions, as well as joint inversion of the receiver functions and Rayleigh wave group velocities. Preliminary results show that anomalously thin crust occurs beneath Northwest Scotland, directly above an area of anomalously slow mantle.



Virtual seismograms for the earthquake (red star) are constructed for each of the stations marked by triangles using data recorded on the seismometer array (blue dots). The blue seismograms are the observed signals and the red seismograms are the reconstructions.

Susanne Sargeant and Brian Baptie visited Kazakhstan in May 2013, as part of the Earthquakes Without Frontiers (EWF) project. The aim of the visit was to develop relationships between the two agencies involved in national seismic hazard assessments, the Kazakh Institute of Seismology and the Kazakh Institute of Geophysics. This led to agreements to collaborate and a visit to BGS by Natalya Silacheva of the Institute of Seismology. EWF is a NERC funded consortium research project led by the University of Cambridge into improving resilience to natural hazards. The project started in 2012 and will continue until 2017. BGS are contributing to research on ground motion modelling and seismic hazard assessment, and to the wider trans-disciplinary process.

Roger Musson is continuing to work with researchers from the University of Edinburgh and University College London as a co-investigator in the RACER (Robust Assessment and Communication of Environmental Risk) project, a whole-systems approach to uncertainty in seismic hazard. The research is part of the NERC Probability, Uncertainty & Risk in the Environment (PURE) initiative.

BGS and Istituto Nazionale di Geofisica e Vulcanologia (INGV) Milan have completed the Global Historical Earthquake Archive project, which was commissioned by the Global Earthquake Model (GEM).

Susanne Sargeant visited Myanmar in August/September 2013 to help provide training in various aspects of earthquake risk and risk management. A key part of this was for staff to know what to do in an earthquake and how to work in and around damaged buildings. An important objective of the training was to encourage staff to think about the risk from earthquakes and how they might manage it.

In August 2013, Heiko Buxel assisted researchers from University College Dublin install two small seismic arrays immediately east of Vatnajokull on Iceland, close to Laki volcanic system. Volcano. 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.

Richard Luckett visited Kenya in March 2014 to install and provide training in the SEISAN seismic analysis software for the Geothermal Development Company in Kenya. This will assist with the study of induced seismicity during geothermal energy production.

BGS data are exchanged with other agencies to help improve source parameters for regional and global earthquakes. Phase data are distributed to the (EMSC) to assist with relocation of regional earthquakes and rapid determination of source parameters. Phase data for global earthquakes are sent to both the National Earthquake Information Centre (NEIC) at the USGS and the International Seismological Centre (ISC). This year, data from 487 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. Our web pages include 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 1,095,000 visitors logged in the year (over 10.1 million hits). Significant peaks (up to ten times the daily average) were observed following the Bristol Channel earthquake of 20 February 2014 (18,000 visitors), and the Lleyn Peninsula earthquake of 29 May 2013 (20,000 visitors).

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.

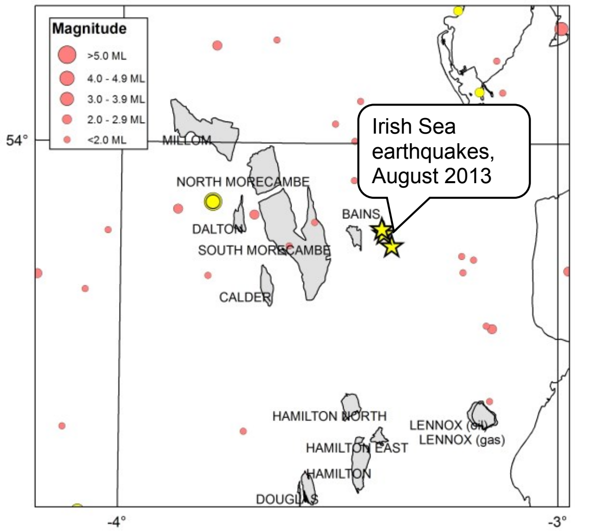
The SEP seismometer used in the School Seismology Project.

The aim of the UK School Seismology Project (UKSSP) is to develop specific resources for teaching and learning seismology in UK schools. These include 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. This provides teachers and students with the excitement of being able to record their own scientific data and help students conduct investigations using their own data.

Earthquake Teachable Moments is a project that provides information about topical earthquakes for schoolteachers, students and the public. The project is led by the University of Liverpool, with support from the British Geophysical Association, the UK School Seismology Project and the British Geological Survey. In the hours following a significant earthquake, seismologists create slideshows detailing key facts such as the earthquake's location, the region's historical seismicity, its tectonic setting, and damage caused. The slideshows also incorporate seismograms of the earthquake from the British Geological Survey's network of instruments as well as from the School Seismometer network.

The 2013 BGS Open Day attracted 993 visitors with many of them visiting the interactive earthquake display.

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 2013-2014, at least 986 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 2013, published and distributed in Galloway (2014).

There were 214 local earthquakes located by the monitoring network during 2013-2014, with 30 having magnitudes of 2.0 ML or greater, and six having magnitudes of 3.0 ML or greater. Fourteen events with a magnitude of 2.0 ML or greater were reported felt, together with a further 72 smaller ones, bringing the total to 86 felt earthquakes in 2013-2014. Note that 65 of the felt earthquakes were related to mining induced seismicity around Ollerton, Nottinghamshire.

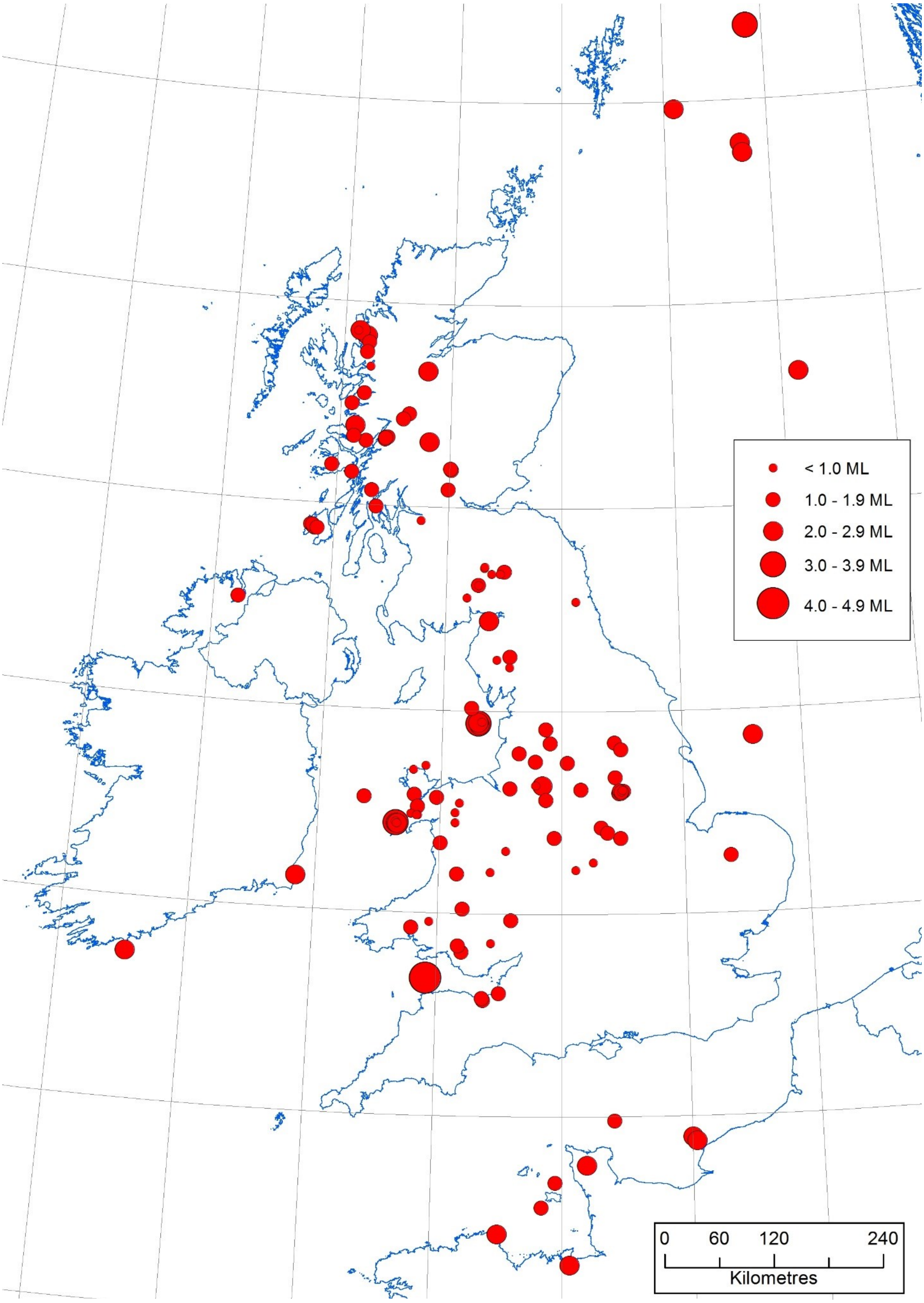
The largest earthquake in and around the British Isles during 2013-2014 was a magnitude 4.1 ML event in the Bristol Channel. The earthquake occurred on 20 February 2014 at 13:21 UTC, with an epicentre approximately 18 km NNW of Ilfracombe, Devon, and 33 km SW of Swansea, Wales. The earthquake was widely felt across southwest England and south Wales with a maximum observed intensity of 5 EMS. This was the largest earthquake to have occurred in the vicinity since a magnitude 3.6 ML earthquake off Hartland Point on 31 May 2001.

A magnitude 3.9 ML earthquake occurred on 29 May at 03:16 UTC approximately 2 km 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 on 29, 30 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 3.3 ML earthquake was recorded in the Irish Sea on 25 August at 09:58 UTC, with an epicentre approximately 25 km west of Fleetwood, Lancashire. This event was preceded by a magnitude 2.5 ML foreshock in the same location at 05:37 UTC and followed by a magnitude 2.8 ML aftershock on 31 August. These were the largest earthquakes to have occurred in the Irish Sea since a series of three earthquakes, with magnitudes of 3.8, 4.1 and 5.0 ML, on 16 and 17 March 1843.

BGS received over 60 reports from members of the public who felt the earthquake. Almost all of these came from inhabitants of the Lancashire coast at distances of up to 40 km from the epicentre.

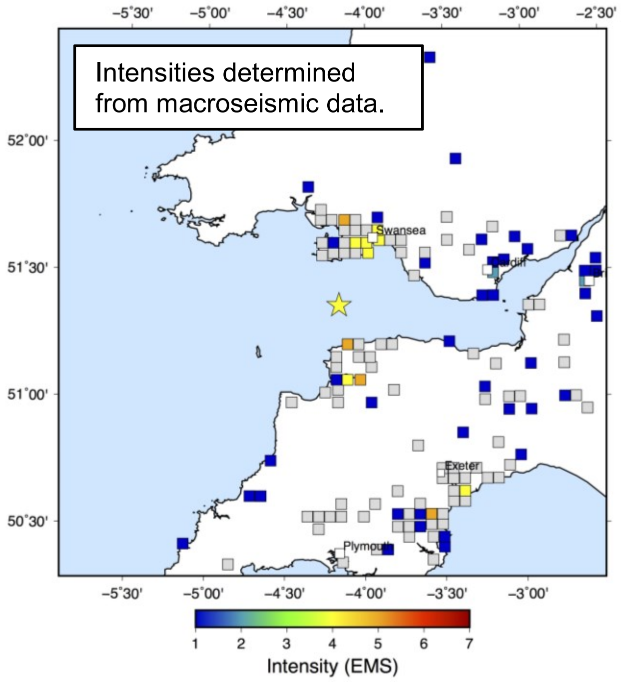
The epicentres were immediately east of the Bains gas field, leading to speculation that these earthquakes could have been related to hydrocarbon production. However, the Bains field ceased production in 2009, and although there is a long history of induced earthquakes related to gas extraction in places such as Groningen, Netherlands (van Eijs et al, 2006), the historic earthquakes in the area show that natural seismicity predates any production.



Epicentres of all earthquakes in and around the UK detected in the reporting period (1 April 2013 – 31 March 2014).

Seismic Activity

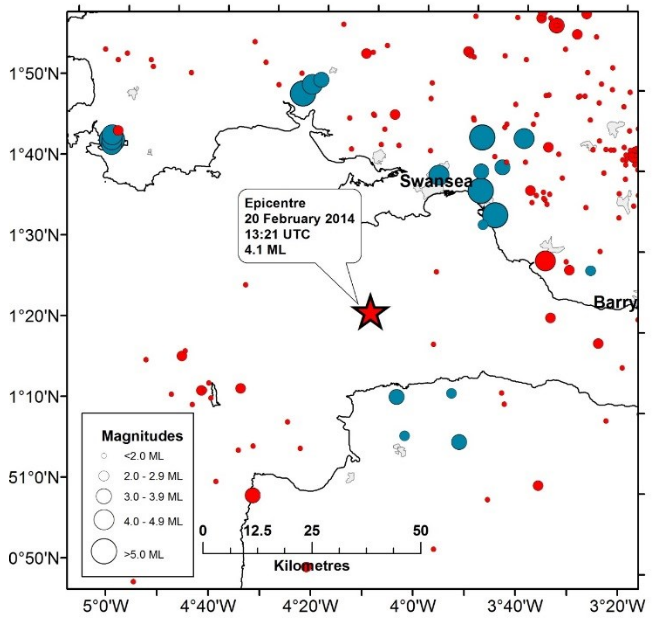
The Bristol Channel Earthquake



Significant media and public interest was generated on 20 February 2014 following a magnitude 4.1 ML earthquake in the Bristol Channel. It was widely felt across southwest England and south Wales with a maximum observed intensity of 5 EMS.

The earthquake occurred on 20 February 2014 at 13:21 UTC, with an epicentre approximately 18 km NNW of Ilfracombe, Devon, and 33 km SW of Swansea. The instrumental magnitude was determined at 4.1 ML, and initial reports suggested that the earthquake had been felt widely across southwest England and south Wales. This was the largest earthquake to have occurred in the vicinity since a magnitude 3.6 ML earthquake off Hartland Point on 31 May 2001.

373 members of the public from 168 places completed our online macroseisemic questionnaire, allowing EMS intensity to be calculated in different locations. A maximum intensity of 5 EMS was observed on the north coast of Devon, while intensities of 4 EMS were observed in Swansea and Barnstable. Elsewhere, there was generally insufficient data to reliably calculate intensity, however, the earthquake was widely felt at distances of up to 125 km from the epicentre, namely from the whole of Devon, Somerset, western Gloucestershire, Glamorganshire and Monmouthshire. A few reports were received from around Cheltenham, Swindon and Guilford (between 150 and 250 km to the east of the epicentre).

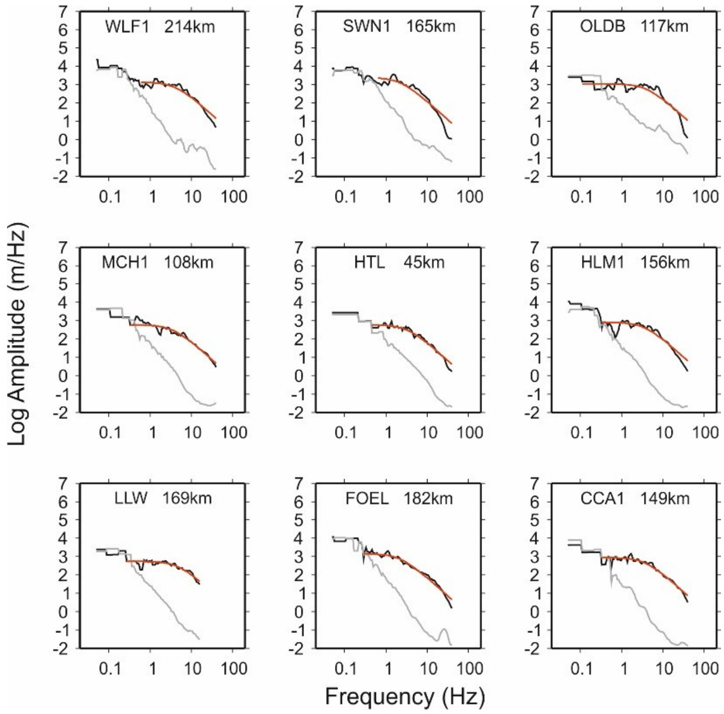


Instrumental (red) and historical (blue) seismicity in the Bristol Channel area.

The area over which an earthquake with a magnitude of 4.1 ML, and depth of 5 km, might be felt, calculated using the intensity attenuation relationship derived for the UK by Musson (2005) is around 200 km from the epicentre (at intensities of up to 2 EMS). This agrees reasonably well with the observed data.

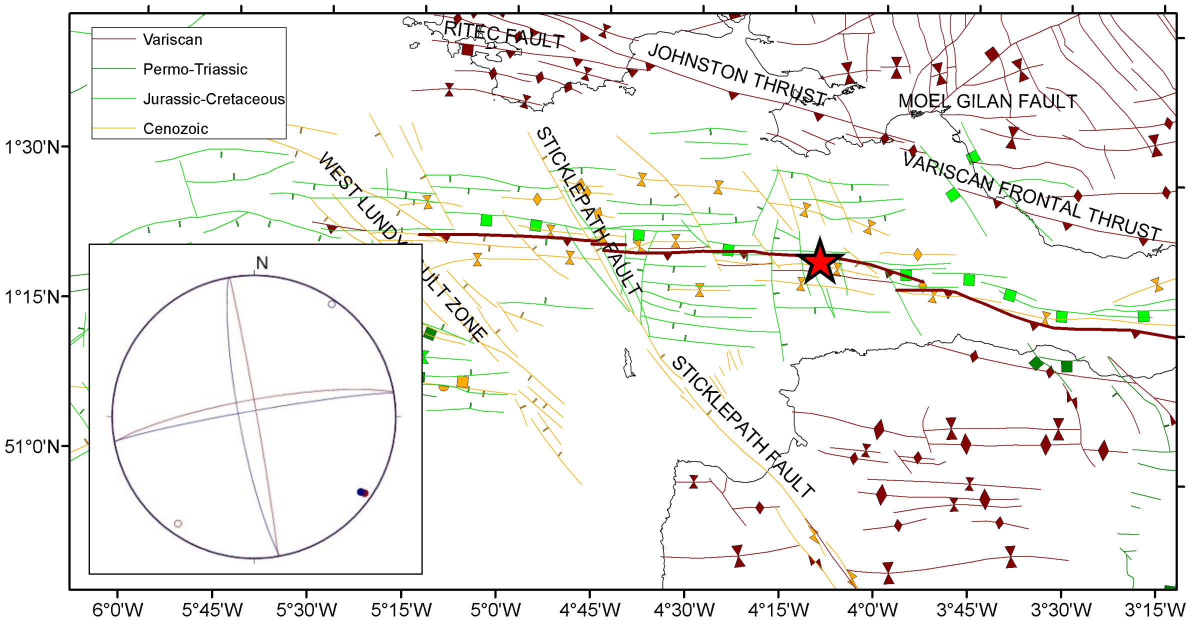
Most people described the shaking strength of the earthquake to be either weak or moderate, with mainly a trembling effect, whilst others described the effect as swaying or jerky. About half of the reports described the sound strength as being faint-moderate. About one third of the reports stated that windows rattled and/or crockery and furniture shook.

Seismic moment and stress drop were determined 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 results give a moment M_0=1.58x10^{14} Nm, a stress drop $\Delta\sigma$ = 14.2 ± 8.8 bars, and a moment magnitude M_w = 3.4 ± 0.2. The latter is less that the value of 3.8 obtained by conversion of the local magnitude (4.1 ML) using the relationship of Grunthal et al (2009). Peak ground accelerations of 0.2 – 0.3 mm/s^2 were recorded at distances of 48 – 177 km from the epicentre. Stochastic modelling (Boore, 2005) suggests that these are consistent with the calculated seismic moment and stress drop.



Observed (black) and modelled (red) displacement spectra at a range of distances. The grey line shows the noise spectrum.

A focal mechanism was calculated from first motion and amplitude data using two different methods: Snoke (1984); and Hardebeck and Shearer (2003). Both give similar results showing either left-lateral strike slip faulting along a near north-south striking fault plane, or right lateral faulting on a near east-west striking fault plane. The earthquake epicentre lies close to the Bristol Channel Fault Zone, a south dipping thrust structure of Variscan age that runs approximately east-west through the Bristol Channel. Numerous extensional faults of Mesozoic age, associated with the development of the Bristol Channel basin, run sub-parallel to the Bristol Channel Fault Zone. In addition, there are a number of near north-south striking faults of Mesozoic and Cenozoic age that cut across the Bristol Channel Fault Zone. Reactivation of faults with either of these orientations could result from stresses associated with present day deformation, i.e. northwest-southeast compression.



Observed faulting in the vicinity of the epicentre (red star). Faults are coloured by age. The Bristol Channel Fault is shown by the bold red line. The inset shows focal mechanisms calculated using Snoke et al (1984) (red line) and Hardebeck and Shearer (2003) (blue line)

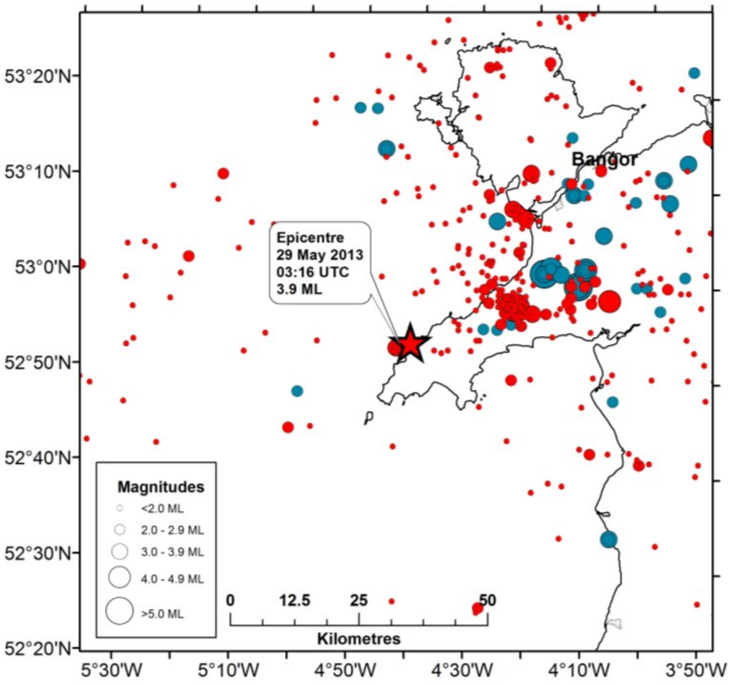
Seismic Activity

The Lleyn Peninsula Earthquake

A magnitude of 3.9 ML earthquake occurred on 29 May at 03:16 UTC approximately 2 km off the northern coast of the Lleyn Peninsula, Gwynedd. The earthquake was widely felt in North Wales and as far afield as Dublin to the west and Blackpool to the northeast.

The earthquake of 29 May 2013 occurred at 03:16 UTC (04:16 BST), with an epicentre approximately 13 km NW of Abersoch, Gwynedd. The instrumental magnitude was determined at 3.8 ML. The earthquake was located approximately 21 km WSW of the magnitude 5.4 ML earthquake that occurred on 19 July 1984, which is the biggest ever recorded onshore in the UK. The earthquake on 29 May 2013 was approximately 256 times smaller than the 1984 earthquake.

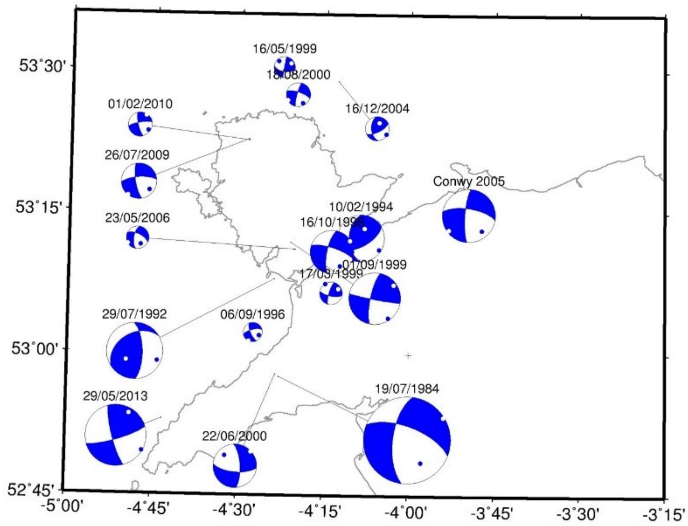
Over 514 members of the public from 173 places completed our online macroseismic questionnaire, allowing EMS intensity to be calculated in different locations. A maximum intensity of 5 EMS was observed. The majority of the reports came from within a 50 km radius of the epicentre, from Abersoch, Caernarfon, Bangor, Holyhead and their surrounding hamlets. We also received reports from: Conwy and Rhyl (75-100 km NE of the epicentre); Cardigan and Fishguard (85-100 km south of the epicentre); Liverpool, Southport, Blackpool and Oldham (100-140 km NE of the epicentre); the Isle of Man (150 km north of the epicentre); near Newry, Northern Ireland (150 km north of the epicentre); and towns down the east coast of Eire from Dublin to Gorey, Wexford (110-120 km west of the epicentre).



Instrumental (red) and historical (blue) seismicity in the Lleyn Peninsula area.

The estimated area over which an earthquake with a magnitude of 3.8, and depth of 10 km, might be felt (at intensity 2 EMS) was calculated to be a distance of up to 150 km from the epicentre. Analysis of the results from an automatic online questionnaire survey agrees with this.

Many people described being woken from their sleep by shaking. A number of people also heard a loud sound. Many of the reports stated that windows and crockery rattled. Reports received included “the bed was shaking”, “loud rumbling sound woke me” and “woke the household and many neighbours”. Three aftershocks were recorded between 29, 30 and 31 May, with magnitudes of 1.7, 0.8 and 1.7 ML,



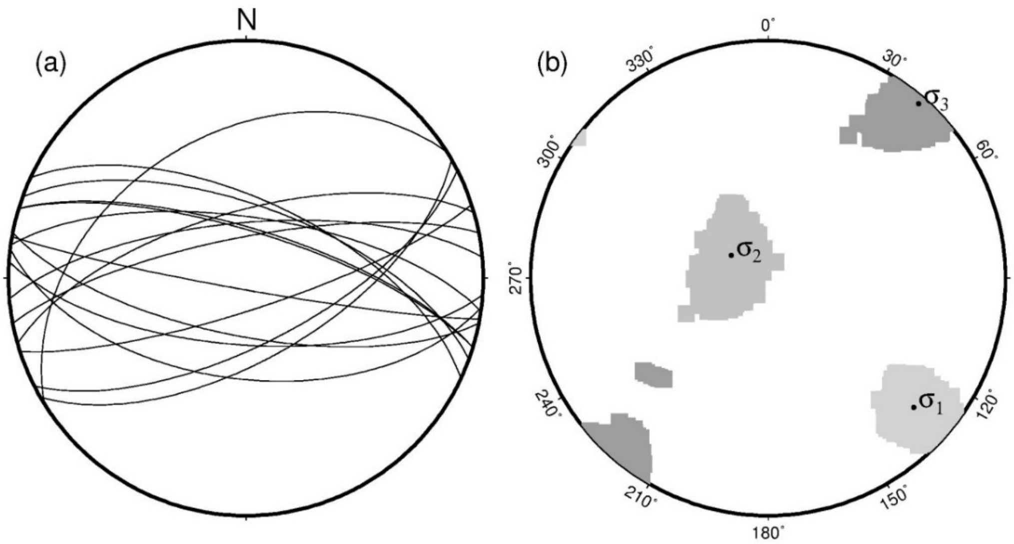
Focal mechanisms determined for earthquakes in North Wales show mainly northwest-southeast compression.

respectively, all of which were reported as felt by a small number of people.

A focal mechanism was calculated for the 29 May earthquake using the grid search method of Snoke et al. (1984). This shows either left-lateral strike slip faulting along a near north-south striking fault plane, or right lateral faulting on a near east-west striking fault plane. This is similar to other mechanisms for earthquakes in the region, which are mainly strike-slip with northwest-southeast compression and northeast-southwest tension, or reverse, with northwest-southeast compression. This results in dips for the P axes that are sub-horizontal, while the T axes vary from horizontal to vertical. The P-axes orientations for most events cluster around the southeast.

Baptie (2013) estimated stress orientations for North Wales earthquake data by inverting the fault plane orientations and slip directions using the technique of Michael (1984, 1987a). The selected fault planes were those closest to the predominantly observed east-northeast trend. Confidence regions were determined using a bootstrap technique (Michael, 1987b), in which 2000 bootstrap resamplings were used. In addition, the focal mechanisms in the bootstrap resampling are randomly flipped 20% of the time, to allow for incorrect fault planes in the data.

Inversion results for the data set using the east-west fault planes suggest that both σ_1 and σ_3 are near horizontal and trend approximately northwest-southeast and northeast-southwest, respectively. This should lead to strike slip faulting. The average angular misfit between the data and the tangential traction is only 9° and the 95% confidence limits are relatively small (approximately ±10°).



Preferred fault planes (a), chosen to match a priori geological observations, and results of the linear inversion (b) showing the maximum (σ_1), intermediate (σ_2) and minimum stress directions (σ_3). The shaded area in (b) shows the 95% confidence intervals obtained by bootstrap resampling. The average angular misfit is 9°.

Seismic Activity

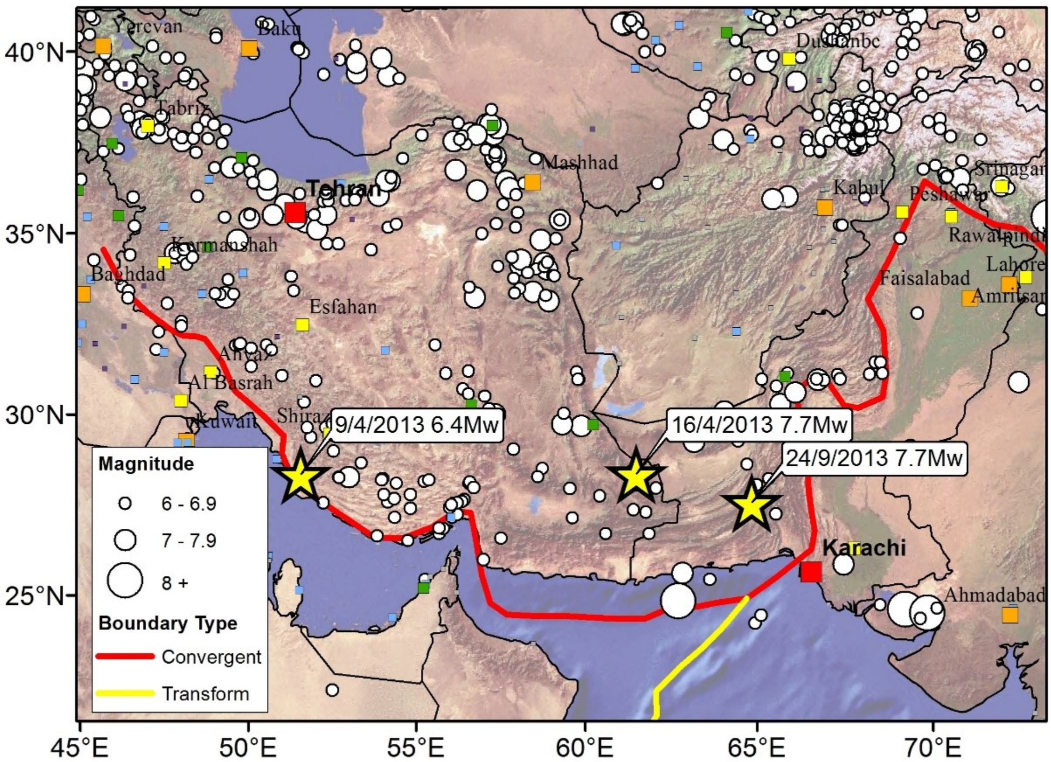
Overview of global earthquake activity

Worldwide, there were fourteen earthquakes with magnitudes of 7.0 or greater and 139 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.

Southeast Iran was struck by a magnitude 7.7 earthquake on 16 April 2013 close to the city of Khash. This was the largest earthquake to strike Iran in over 40 years. The earthquake caused at least 35 deaths in Pakistan's Balochistan province and was over 100 times stronger than a 6.4 magnitude quake that struck southwest Iran on 9 April near the nuclear plant at Bushehr, killing at least 37 people.

The earthquake occurred as a result of normal faulting in the subducting Arabian plate rather than the over-riding Eurasian plate and the depth of approximately 80 km beneath the Earth's surface was significant in rather less damage than might have been expected for an earthquake of this size. The Arabian plate is subducted beneath the Eurasian plate at the Makran coast of Pakistan and Iran, and becomes progressively deeper to the north. Such earthquakes are relatively rare, although the subducted Arabian plate is known to be seismically active to depths of about 160 km.

On 24 September 2013, a magnitude 7.7 earthquake struck Balochistan province, a remote part of southwest Pakistan, 66 km



The yellow stars show the locations of three significant earthquakes that occurred in Iran in 2013. The white circles shows earthquakes from the BGS World Seismicity Database. Symbols are scaled by magnitude. The coloured lines show plate boundaries.

from the city of Awaran and approximately 280km northwest of Karachi. Reports at the time suggested that over 800 people were killed and many buildings were destroyed. The earthquake resulted from oblique strike-slip faulting as a result of both the oblique motion of the Indian sub-continent with respect to Eurasia and the northwards motion of Arabia.

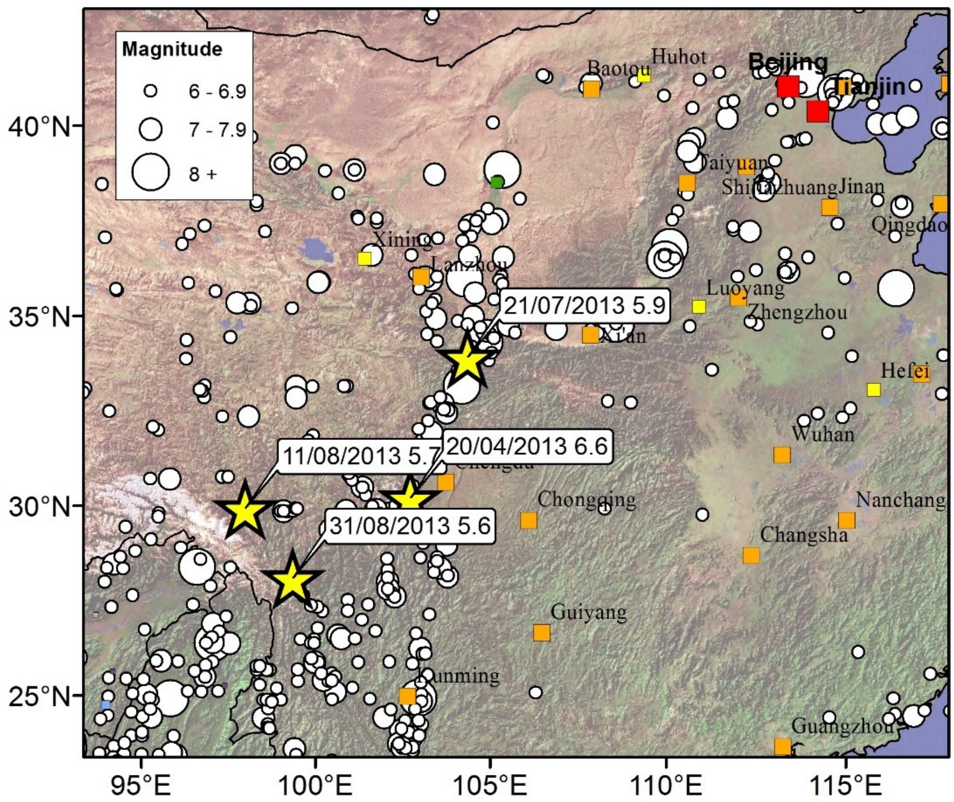
A magnitude 6.6 earthquake struck Sichuan province on 20 April 2013. China's official Xinhua news agency reported that at least 193 people died in the earthquake, more than 11,000 were injured, and around 13,000 homes were destroyed in several townships in the region. The earthquake was located approximately 90 km SSW of the magnitude 7.9 Sichuan earthquake, which occurred on 12 May 2008 killing over 89,000 people and causing injury to some 375,000 others.

A magnitude 5.9 earthquake struck in Gansu province in northwest China on 21 July 2013. Reports suggested that as many as 95 people were killed, over 1,000 were injured, around 2,000 houses collapsed and another 22,000 buildings were damaged. The epicentre was near the city of Chabu.

Eastern Tibet was struck by a magnitude 5.7 earthquake on 11 August that injured at least 87 people and over 45,000 houses were damaged in the counties of Markam and Zogang in Chamdo Prefecture. Damage to roads by earthquake triggered landslides was also reported.

Yunnan province was struck by a magnitude 5.6 earthqukae on 31 August. Reports from the Yunnan Earthquake Prevention and Disaster Reduction Centre stated that three people were killed and 40 others were injured in Deqin County. It was also reported that at least 600 homes were destroyed and 55,000 others were damaged in the region.

The largest earthquake of the year was a magnitude 8.3 event that occurred in the Sea of Okhotsk, immediately east of the Kamchatka Peninsula on 24 May. A deep focus of approximately 600 km meant that damage was limited, however, it was felt strongly over 7000 km away in Moscow.



The yellow stars show the locations of significant earthquakes that occurred in China in 2013. The white circles shows earthquakes from the BGS World Seismicity Database. Symbols are scaled by magnitude.

Scientific Objectives

Evaluation of Array Detections

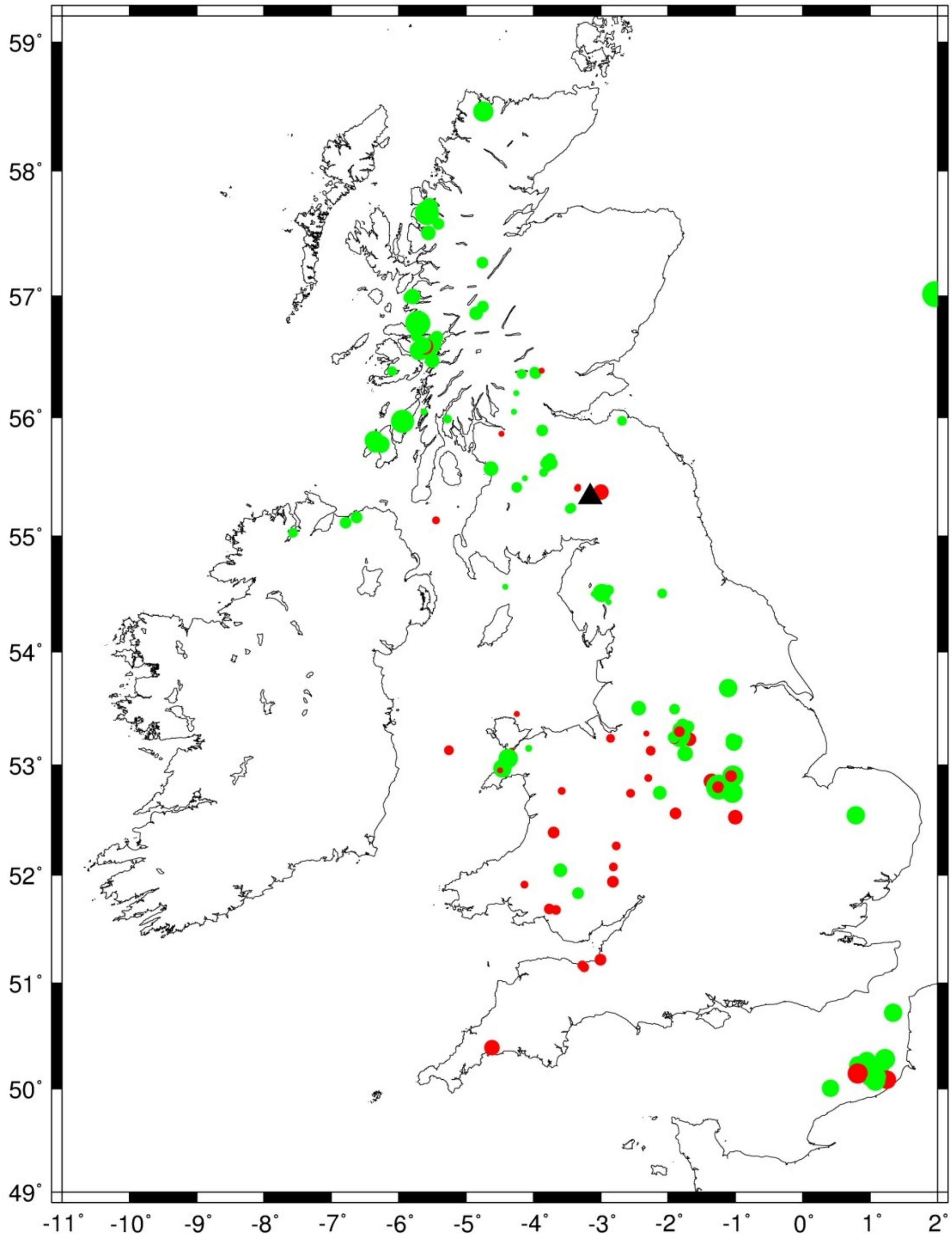
The Atomic Weapons Establishment (AWE) operates a seismic array at Eskdalemuir in the Scottish borders as the UK contribution to the International Monitoring System of the Comprehensive Test Ban Treaty. Recently, scientists at AWE Blacknest have been running advanced triggering algorithms at the array to detect local earthquakes. The resulting detections have been systematically compared with those detected by the BGS seismic network.

The Eskdalemuir seismic array (EKA) comprises of 20 seismometers in a cross formation spread over an area 10 km^2. Installed in 1962, it is one of the oldest seismic arrays in the world and is part of a global network used to monitor nuclear tests by the Comprehensive Test Ban Treaty Organisation (CTBTO). The EKA array is operated by AWE Blacknest, based at Aldermaston. The seismologists at Blacknest are, among other things, concerned with maximising the usefulness of EKA. Recently, a project has been carried out by Neil Selby to use the array to detect local earthquakes. From a CTBTO perspective these are noise and need to be discriminated against.

Once a plane wave is identified crossing a seismic array it is relatively simple to calculate the azimuth it is coming from and the velocity it is travelling at (which in turn indicates which seismic phase is being recorded). Once these parameters are known the traces at the different stations can be stacked, greatly improving the signal-to-noise ratio. The difficult part is recognising that very small signals at individual stations are the same phase. Methods developed at Blacknest include minimum noise spatial filters that efficiently remove noise using noise models (Douglas, 1998). Combining such filters with a grid-search algorithm allows very small signals to be identified. In general, all that is known of these signals is the direction that they come from and their velocity, so it is interesting to find out whether they originate from known earthquakes, previously undetected earthquakes or coherent noise of some type.

Although BGS receive real-time data from EKA we do not have access to the software developed at Blacknest. For the purpose of this evaluation, we were provided with one year of array detections. First, every earthquake or explosion with a location in the BGS database was checked to establish whether an array detection existed - 125 of the 164 events have corresponding BGS detections (see map). The array detects events in Scotland more consistently than events a similar distance away to the south. This is presumably because more noise is present on southern azimuths. Two events close to the array were not detected because the plane wave assumption made by the algorithm breaks down at short distances.

Secondly an attempt was made to associate each array detection with an event in the BGS database. Only a month of detections were checked, as many small explosions, which are identified but not located routinely by BGS, had to be located for the first time, and searches were made for time periods when no BGS events had been detected. The 90 array detections correspond to 48 events with no false triggers. Of these events 15 were previously undetected (by BGS) small quarry blasts and one was a 0.7 ML earthquake near Stirling, which was added to the BGS database.



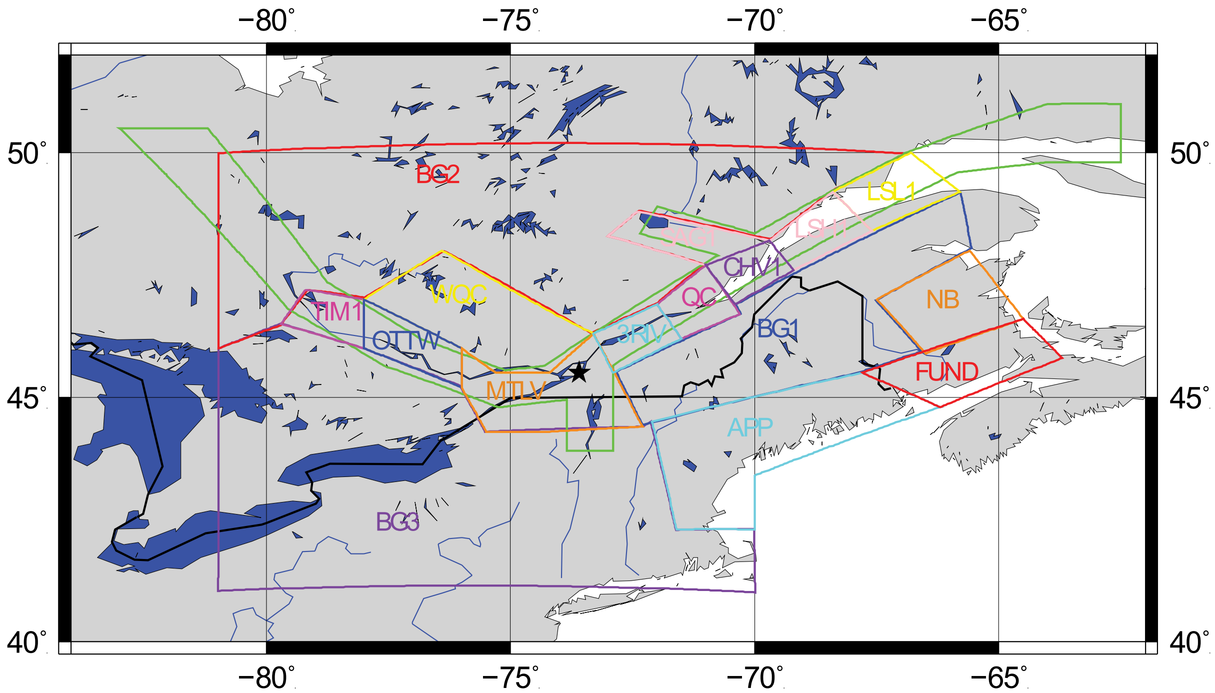
Earthquakes and quarry blasts detected by the national network and located between July 2012 and June 2013. The green circles represent events detected by EKA, the red ones events for which no EKA detection was made, the circles are scaled by the magnitude of the events. The black triangle in southern Scotland is the location of EKA.

Benchmarking Recent PSHA Approaches

Seismic hazard 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 (PSHA) have been published. Often, different criteria are used for characterizing the source zone model or for selecting the most suitable ground motion models for the study area. Furthermore, different software can be used for computing the hazard. Here, we compare two approaches and compare the resulting differences given the same source model.

In this study we compare two different methods for calculating seismic hazard: OpenQuake, produced by Global Earthquake Model initiative (Pagani at al., 2014; Silva et al., 2013); and, M3C (Musson, 1999; Musson, 2009) a Monte Carlo approach. Openquake uses the classical approach to PSHA developed by Cornell (1968, 1971) and McGuire (1976), and is based on the integration of probability distribution functions over a range of magnitudes, distances and associated uncertainties. M3C is an "observation-based" approach, i.e., it is based on Monte Carlo simulations to generate many synthetic catalogues of seismic events and the corresponding ground-motion parameters. The output is obtained by counting the number of results exceeding a critical value.

To ensure transparency in the comparison, we use the source zone model developed for south-eastern Canada by Atkinson and Goda (2011). This consists of 17 areal sources and is characterised by a



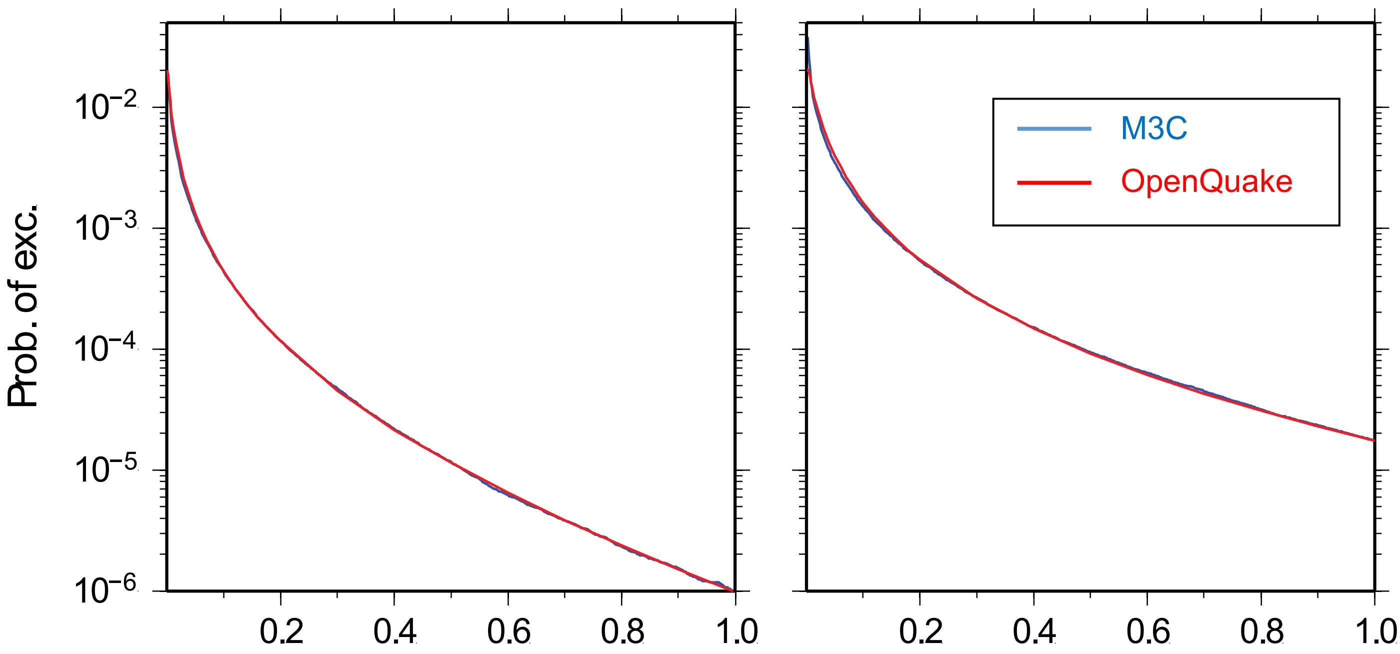
Source zone model of south-eastern Canada. It consist of 17 areal source zones and the site is indicated by a black star.

moderate-seismicity environment. The most active area is the Iapetan Rift (IRM zone), subdivided into nine sub-regions. The most recent 7 Mw earthquake occurred in the Charlevoix region (CHV1 zone) in 1663.

We use a single ground motion prediction equation (GMPE) in both methods, the model developed by Boore and Atkinson (2008), which is suitable for distances up to 200 km and moment magnitudes up to 8.0. Hazard is calculated over a time period of 100 years. M3C generated 1,000,000 simulated catalogues, each with a duration of 100 years, giving a total number of 100,000,000 years.

The computational time required for M3C to generate 1,000,000 synthetic catalogues and to compute a hazard curve is approximately six minutes on a desktop PC. The OpenQuake software was developed to run on multiple processor cores, with its engine distributing the job automatically across available processors. In this case, four processor cores were used, taking approximately 15 minutes to compute a hazard curve for south-eastern Canada. As expected for this relatively simple calculation, the running time is longer for OpenQuake than for M3C.

We obtained both hazard curves and seismic maps from both methods. The agreement between M3C and OpenQuake is excellent for both cases. This is in good agreement with the conclusions of Musson (1998), who states that the Monte Carlo simulation and Cornell-McGuire methods should be entirely compatible with each other and their results are identical if the source zone model is the same.



Annual probability of exceedance as a function of PGA and spectral accelerations at a period of 0.2 s computed by M3C (blue lines) and OpenQuake (red lines). The source zone model is for south-eastern Canada.

Scientific Objectives

Ground Motions from Small Earthquakes

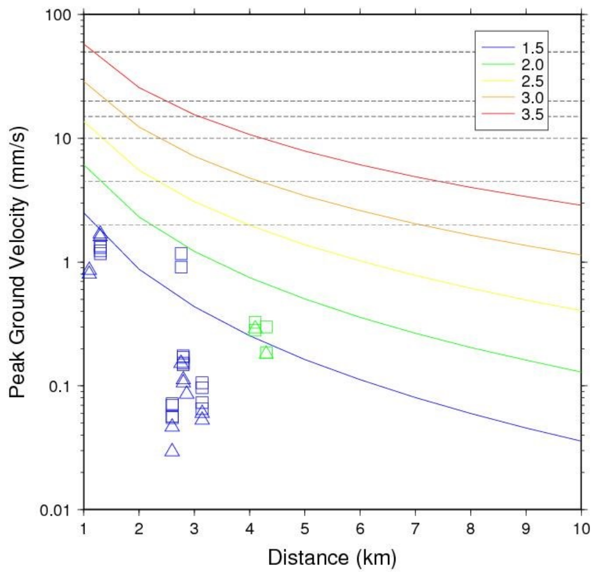
Recent examples of induced seismicity during shale gas exploration and production have highlighted the need for effective regulation to mitigate this hazard. This requires the definition of implementable thresholds for acceptable ground vibrations. Here, we use numerical modelling to explore possible ground motions for small to moderate earthquakes and compare these with existing regulations for vibrations from blasting.

We used the stochastic approach (Boore, 1983) and the SMSIM software (Boore, 2005) to compute ground motion estimates. This requires detailed parameters to characterise the source, path and site effects. Here, we calculate seismic moment directly from earthquake magnitude (Hanks and Kanamori, 1979) and we assume that for small magnitudes local magnitude ML is approximately equal to moment magnitude Mw. We use a single corner frequency model for the shape of the source spectrum (Brune, 1970).

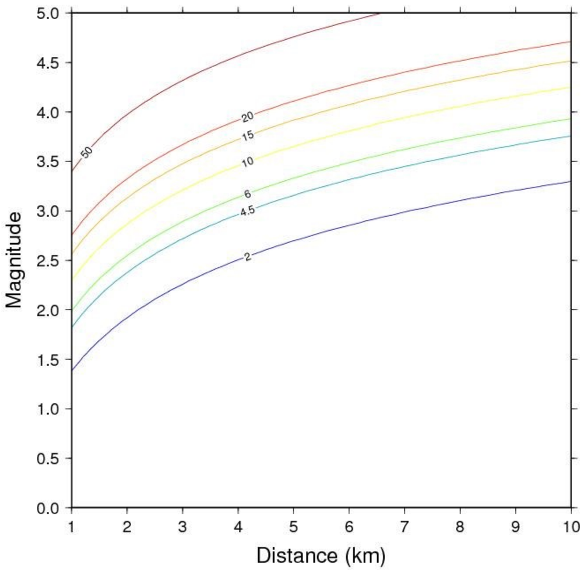
Stress drop is an important parameter in the dynamics of the rupture process and can have a strong effect on recorded ground motions. However, most earthquakes have stress drops in the range of a few MPa to a few tens of MPa. Here, we assume a fixed stress drop of 3 MPa.

At short hypocentral distances geometrical spreading is dominated by the body wave term and we use the path attenuation quality factor determined for the UK by Sargeant and Ottemoller (2009). We do not consider either site specific attenuation or amplification.

The resulting models of ground velocity as a function of hypocentral distance calculated for earthquakes with different magnitudes can be compared with the two limits for ground vibrations set out in two British Standards (BSI, 1993 and BSI, 2008). BS 6472-2 gives guidance on acceptable limits for human exposure to blasting. The limits are 6-10 mm/s during the working day, 2mm/s at night time and 4.5mm/s at other times. BS 7385-2 specifies limits for vibrations caused by blasting, above which cosmetic damage



Modelled peak ground velocity (solid coloured lines) plotted as a function of hypocentral distance .The grey dashed lines show the limits for acceptable vibrations from blasting specified in BS 6472-2 and BS 7385-2. The squares and triangles show observed horizontal and vertical ground motions.

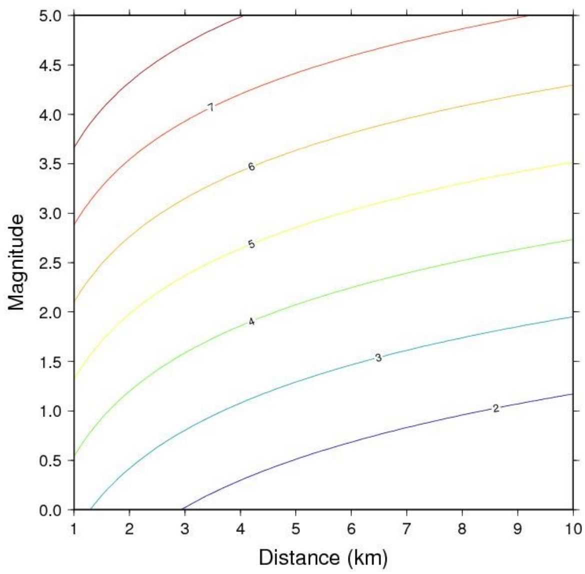


Peak ground velocity calculated for a range of earthquake magnitudes and hypocentral distances. The curves show the fixed values of peak ground velocity given by BS 6472-2 and BS 7385-2.

could take place. This gives limits of 15 mm/s at 4 Hz, increasing to 20 mm/s at 15 Hz and 50 mm/s at 50 Hz. It is clear that only the largest earthquakes approach the limits for cosmetic damage set out in BS 7385-2 and only at very short distances. Earthquakes with magnitudes of 2.5 or less do not exceed the limits for vibration during the normal working day set out in BS 6472-2, though they do exceed the limits for night-time and weekends.

Peak ground velocities calculated for a range of earthquake magnitudes and hypocentral distances using the same method allow us to estimate the magnitudes and distances at which the model exceeds these limits. The limits above which cosmetic damage could occur (BS 7385-2) are only exceeded for earthquakes with magnitudes of 3 or above within a few kilometres of the hypocentre. This seems reasonably consistent with observations that the largest mining-induced earthquakes, with magnitudes of around 3.0 ML, caused some superficial damage (Westbrook et al., 1980; Redmayne, 1998) including, minor cracks in plaster and harling.

Macroseismic intensity (EMS) can also be calculated as a function of magnitude and distance using the intensity attenuation relationship derived for the UK by Musson (2005). The 6 EMS contour, the level at which some slight damage might occur, appears at magnitudes of just over 2.0, whereas the 15 mm/s limit for cosmetic damage appears at a slightly higher magnitude of 2.5 ML. This raises the possibility that intensity calculations are overestimated, perhaps, because there are relatively few observations at such small hypocentral distances, which might result in the attenuation function being relatively poorly constrained.



EMS Intensities for a range of earthquake magnitude and hypocentral distance

Scientific Objectives

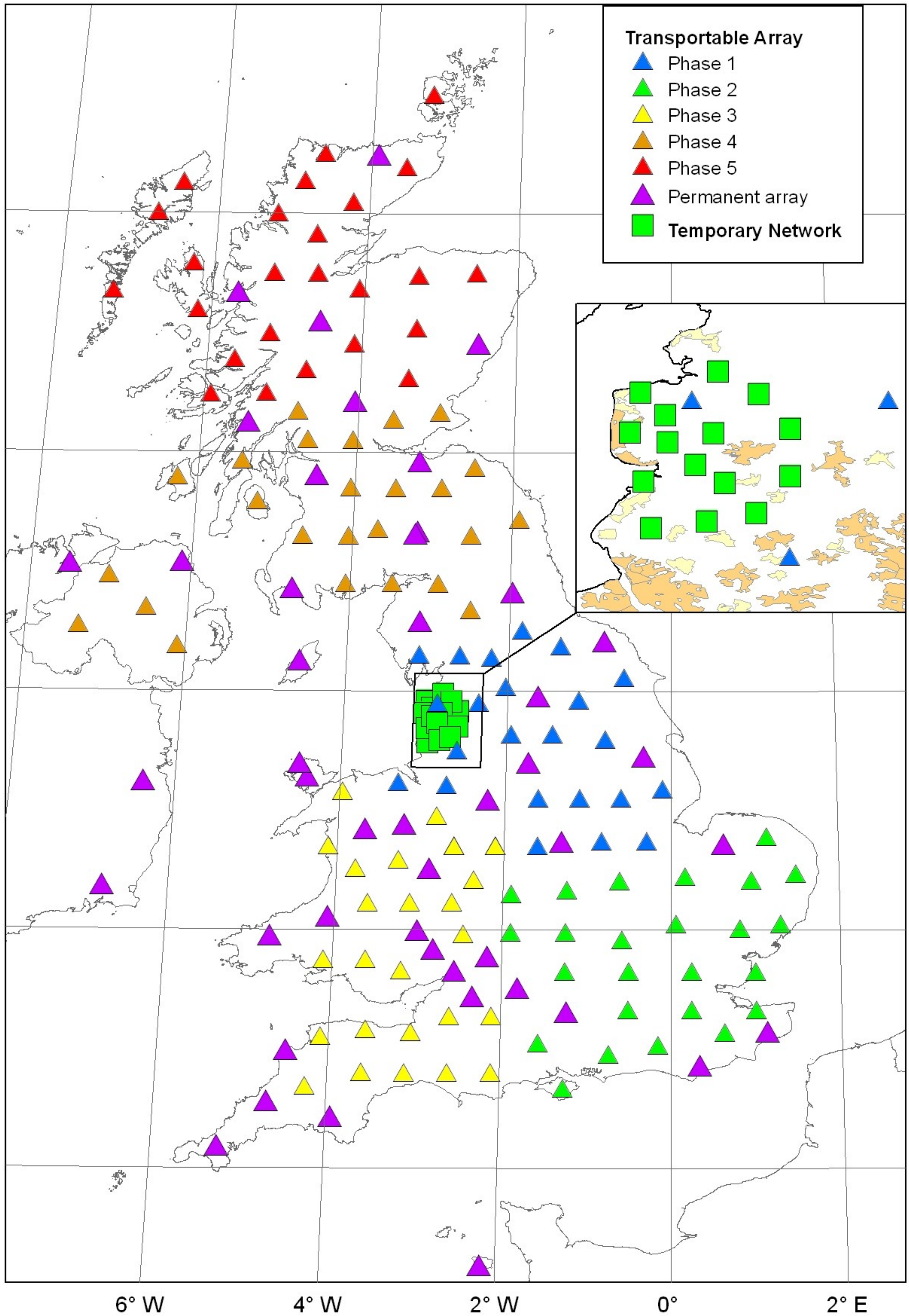
UKArray

In the UK, images of the Earth's crust cannot resolve details less than several tens of kilometres across due to the limited number of sensors in the permanent UK seismic monitoring network operated by the British Geological Survey. This similarly limits our ability to detect and locate small earthquakes, and to interpret or attribute them to specific fault zones, and to either natural or industrial activity.

The recent 'traffic-light' system outlined by DECC (2013) will require hydraulic fracture stimulation ('fracking') to cease if earthquakes with a magnitude of 0.5 or greater occur. However, the existing network of permanent seismic sensors in the UK cannot reliably detect events of magnitude lower than 2.0 and there are several thousands of earthquakes of magnitude 0.0 to 1.9 ML that will be undetected each year in the UK. This highlights the urgent need to improve our capability to detect small earthquakes in order to support and regulate industrial activities. In addition, operators will only be required to monitor during fluid injection, and over a limited area, although recent studies have shown that the monitoring should be for much longer (~2 years after cessation of fluid injection) and over a broader area (~20km^2) to fully characterise the true nature and extent of any induced seismicity.

UK Array is an experiment that aims to address this by deploying a temporary array of 40 sensors that moves progressively across the UK, over a period of several years, with each sensor spending a number of years in a specific location. The experiment is partly funded by the Natural Environment Research Council (NERC) and will be carried out by the British Geological Survey (BGS) along with researchers from the Universities of Bristol, Edinburgh, Leicester and Liverpool.

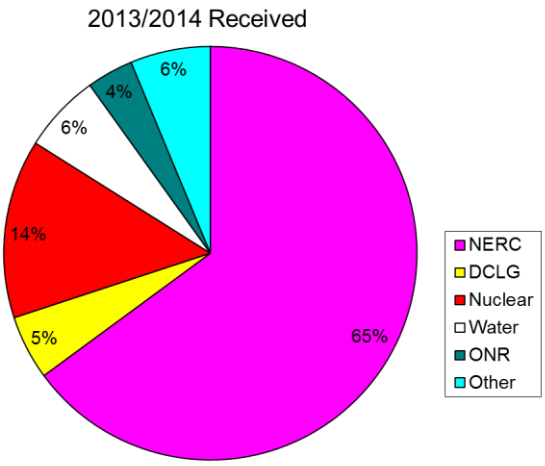
The experiment will provide essential baseline data to enable new research into both the nature and hazard of seismic activity induced by future industrial activities such as fracking operations involved in both conventional and unconventional hydrocarbon exploration and production. For example, new, high resolution information about active fault systems and sub-surface stresses that can be used to identify areas where the hazard from induced earthquakes may be higher. Similarly, constraints on the attenuation of seismic waves in the Earth's Crust under the UK will lead to an improved magnitude scale for small, induced earthquakes and to more effective regulation. The data can also be used to answer fundamental scientific questions about the shallow and deep Earth and to address important issues relating to the future use of the Earth's sub-surface both as a source for sustainable energy and as a means of energy and waste storage. This knowledge will help to inform public perceptions and debate into benefits & hazards of industrial activities.

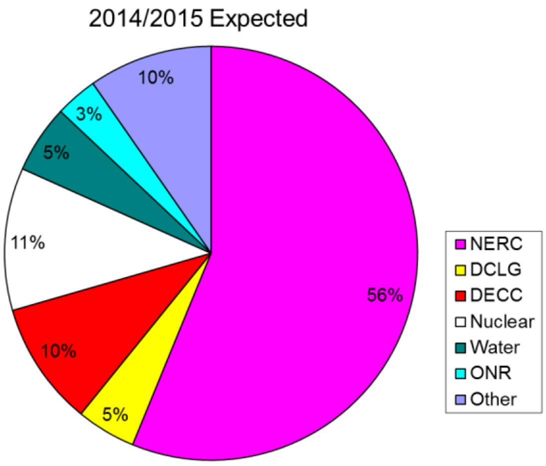


The transportable array progressively covers the entire UK over a period of years. Phase 1 will start in the north of England. A dense network of sensors remains for a longer period in an area of industrial interest such as the Bowland Basin.

Funding and Expenditure

In 2013-2014 the project received a total of £580k from NERC. Some of this was won from specific funding calls. This was matched by a total contribution of £314k from the customer group drawn from industry, regulatory bodies and central and local government.





The projected income for 2014-2015 is slightly greater than that received in 2013-2014, due some aligned projects and additional funding from DECC for the UKArray project. The NERC contribution for 2014-2015 currently stands at £580k, but we hope to increase this through applications for additional funding through the year. The total expected customer group contribution currently stands at £352k. 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).

References

Atkinson, G. M. and Goda, K., 2011.Effects of seismicity models and new ground motion prediction equations on seismic hazard assessment for four Canadian cities. Bulletin of Seismological Society of America, 101, 176-189.

Boore, D.M., 1983. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra, Bulletin of the Seismological Society of America, 73 (6), 1865-1894.

Baptie, B., 2013. Stress field orientation in North Wales: implications for preferred faulting directions. British Geological Survey Commercial Report, CR/13/139.

Boore, D. M., 2005. SMSIM-Fortran programs for simulating ground motions from earthquakes: Version 2.3-A Revision of OFR 96-80-A, U.S. Geological Survey Open-File Report.

Boore, D. M., and Atkinson, G. M., 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01s and 10.0s. Earthquake Spectra, Vol. 24, 99-138.

Brune, J.N., 1970. Tectonic stress and the spectra of seismic shear waves from earthquakes, J. Geophys. Res., 75, 4997-5009.

BSI, 1993. Evaluation and measurement for vibration in 506 buildings — Part 2: Guide to damage levels from groundborne vibration. BS 7385-2: 1993. British Standards Institution, London.

BSI, 2008. Guide to evaluation of human exposure to vibration in buildings — Part 2: Blast-induced vibration. BS 6472-2: 2008. British Standards Institution, London.

Cornell, C.A., 1968, Engineering seismic risk analysis, Bull. Seismol. Soc. Am., 58, 1,583–1,606.

Cornell, C.A., 1971, Probabilistic analysis of damage to structures under seismic loads, in,Howells, D.A, Haigh, I.P., and Taylor, C., eds., Dynamic waves in civil engineering: Proceedings of a conference organized by the Society for Earthquake and Civil Engineering and Dynamics, New York, John Wiley, 473–493.

Department for Energy and Climate Change, 2013. Regulatory roadmap for oil and gas development onshore in the UK, https://www.gov.uk/government/publications/regulatory-roadmap-onshore-oil-and-gas-exploration-in-the-uk-regulation-and-best-practice

Douglas, A., 1998. Making the most of the recordings from short-period seismometer arrays, Bull. Seismol. Soc. Am., 88, 1155–1170.

Grunthal, G., Wahlström, R. and Stromeyer, D., 2009. The unified catalogue of earthquakes in central, northern, and northwestern Europe (CENEC)—updated and expanded to the last millennium. Journal of Seismology, 13, 517–541

Hanks, T. C., and Kanamori, H., 1979. A moment magnitude scale, Journal of Geophysical Research, 84, 5, 2348 - 2350

Hardebeck, J. L. and Shearer, P. M., 2003. Using S/P amplitude ratios to constrain the focal mechanisms of small earthquakes. Bulletin of the Seismological Society of America, 93:2434-2444.

McGuire, R.K., 1976, FORTRAN computer program for seismic risk analysis, U.S. Geological Survey Open-File Report 76-67.

Michael, A.J., 1984. Determination of stress from slip data: faults and folds. J.Geophys. Res. 89 (B13), 11,517-11,526.

Michael, A.J., 1987a.Use of focal mechanisms to determine stress: a control study. J.Geophys. Res. 92 (B1), 357–368.

Michael, A.J., 1987b. Stress rotations during the Coalinga aftershock sequence. J.Geophys. Res. 92 (B8), 7963–7979.

Musson, R.M.W., 1998. On the use of Monte Carlo simulations for seismic hazard assessment, In *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering, Seattle*, paper no. 15, Earthquake Engineering Research Institute.

Musson, R. M. W., 1999. Determination of design earthquakes in seismic hazard analysis through Monte Carlo simulation. Journal of Earthquake Engineering, 3, 463-474.

Musson, R.M.W., 2005. Intensity attenuation in the UK, Journal of Seismology, 9 (1), 73-86

Musson, R. M.W., 2009. PSHA using Monte Carlo simulation: M3C User Guide. CR/07/125.

Ottemöller, L., and Havskov, J., 2003. Moment magnitude determination for local and regional earthquakes based on source spectra. Bulletin of the Seismological Society of America, 93, 203–214.

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva V., Henshaw P., Butler, L., Nastasi, M., Panzeri, L., Simionato., M, and Vigano, D., 2014. OpenQuake engine: An open hazard (and risk) software for the Global Earthquake Model. Seismological Research Letters, Vol. 85(3), 692-702.

Redmayne D.W., Richards J.A. and Wild P.W., 1998. "Mining-induced earthquakes monitored during pit closure in the Midlothian Coalfield", Quarterly Journal of Engineering Geology, 31, 21-36.

Sargeant, S. and Ottemoller, L., 2009. Lg wave attenuation in Britain, Geophys. J. Int., 179 (3) 1593-1606.

Silva V., Crowley, H., Pagani, M., Monelli, D., and Pinho, R., 2013. Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. Natural Hazards.

Snoke, J., Munsey, J., Teague, A. and Bollinger, G., 1984. A program for focal mechanism determination by combined use of polarity and P-SV amplitude ratio data. Earthquake Notes, 55, 3–15.

van Eijs, R., Mulders, F., Nepveu, M., Kenter, C. and Scheffers, B., 2006. Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands, Eng. Geol., 84, 99–111.

Westbrook, G.K., Kusznir, N.J., Browitt, C.W.A. and Holdsworth, B.K., 1980. Seismicity induced by coal mining in Stoke-on-Trent (U.K.), Engineering Geology, 16, 225-241.

Appendix 1 The Project Team

Brian Baptie	Project Manager, observational seismology, passive seismic imaging, induced seismicity
Andy Blythe	Field engineer, installation, operation and repair of seismic monitoring equipment
Julian Bukits	Analysis of seismic events, provision of information to stakeholders
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
John Hume	Installation, operation and repair of seismic monitoring equipment
John Laughlin	Lead 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	Historical earthquakes and seismic hazard
Susanne Sargeant	Seismic hazard and NERC Knowledge Exchange Fellow
Alice Walker	Observational seismology

Appendix 2 Publications

Aspinall, W. and Musson, R., 2014 Selfridge's Seismograph. Seismological Research Letters, 85 (2). 361-364.

Baptie, B., 2013. Stress field orientation in North Wales: implications for preferred faulting directions, British Geological Survey Report, CR/13/139.

Galloway, D., 2016. Bulletin of British Earthquakes 2014. British Geological Survey Internal Report, OR/16/011

Liu, S., Crampin, S., Luckett, R. and Yang, J., 2014. Changes in shear wave splitting before the 2010 Eyjafjallajokull eruption in Iceland. Geophysical Journal International, 199 (1), 102-112.

Musson, R.M.W., 2014. UK seismic hazard assessments for strategic facilities: a short history. Bollettino di Geofisica Teorica e Applicata, 55 (1), 165-173.

Musson, R.M.W., 2014. The seismicity of Ghana. Bulletin of Earthquake Engineering, 12 (1). 157-169.

Musson, R.M.W., 2013. Updated intensity attenuation for the UK. Nottingham, UK, British Geological Survey Report, OR/13/029.

Musson, R.M.W., 2013. A history of British seismology. Bulletin of Earthquake Engineering, 11 (3), 715-861.

Nicolson, H., Curtis, A. and Baptie, B., 2014. Rayleigh wave tomography of the British Isles from ambient seismic noise. Geophysical Journal International, 198 (2), 637-655.

Ottemoller, L. and Sargeant, S., 2013. A local magnitude scale ML for the United Kingdom. Bulletin of the Seismological Society of America, 103 (5), 2884-2893.

Rossetto, T., D’Ayala, D., Gori, F., Persio, R., Han, J., Novelli, V., Wilkinson, S.M., Alexander, D., Hill, M., Stephens, S., Kontoe, S., Elia, G., Verrucci, E., Vicini, A., Shelley, W. and Foulser-Piggott, R., 2014. The value of multiple earthquake missions: the EEFIT L’Aquila Earthquake experience. Bulletin of Earthquake Engineering, 12 (1), 277-305.

Stucchi, M., Rovida, A., Gomez Capera, A.A., Alexandre, P., Camelbeeck, T., Demircioglu, M.B., Gasperini, P., Kouskouna, V., Musson, R.M.W., Radulian, M., Sesetyan, K., Vilanova, S., Baumont, D., Bungum, H., Fäh, D., Lenhardt, W., Makropoulos, K., Martinez Solares, J. M., Scotti, O., Živčić, M., Albini, P., Batllo, J., Papaioannou, C., Tatevossian, R., Locati, M., Meletti, C., Viganò, D. and Giardini, D., 2013 The SHARE European Earthquake Catalogue (SHEEC) 1000–1899. Journal of Seismology, 17 (2). 523-544.

Tappin, D. R., Sibley, A., Horsburgh, K., Daubord, C., Cox, D. and Long, D., 2013. The English Channel ‘tsunami’ of 27 June 2011: a probable meteorological source. Weather, 68 (6).

Appendix 3: Publication Summaries

Selfridge's Seismograph

Aspinall, W. and Musson, R.M.W., 2014.

For several yearsem, Selfridge's store housed a Milne–Shaw seismograph with which the owner, the American, H. Gordon Selfridge, used to create media publicity whenever a major earthquake occurred worldwide. At least four photographs of the installation survive together with an image of an information display chart showing global earthquakes detected by the instrument between 1932 and 1934.

Stress field orientation in North Wales: implications for preferred faulting directions.

Baptie, B., 2013.

In this study, we estimate the stress field in North Wales, including Anglesey, by applying a linear inversion method to a new data set of earthquake focal mechanisms from the region. Confidence regions are determined using a bootstrap technique, in which the data can be resampled hundreds or thousands of times. The strong east-west trend in observed surface faults in North Wales was used to make an initial estimate of the correct fault planes from the two possible planes. Our inversion results suggest that both σ_1 and σ_3 are near horizontal and trend approximately northwest-southeast and northeast-southwest, respectively. This is in good agreement with previous results. Such a compressive tectonic regime, where the intermediate principal stress is vertical and the maximum and minimum principal stresses are horizontal, should lead to predominantly strike slip faulting. There may also be components of either thrust or normal faulting, as indicated by the sub-horizontal orientations of σ_1 and σ_3. Comparison with results where the alternative planes are used suggests that the *a priori* selection gives both smaller misfits and confidence intervals. In addition, the results compare favourably with the results of a grid search method that is allowed to select a preferred fault plane. The stress tensor results suggest that optimally oriented faults are likely to be near vertical and trend either 85° or 185° from North. In addition, faults dipping at 45° and trending at 50° from North are also optimally oriented with respect to the stress field. However, a wide range of pre-existing faults that are less optimally oriented could also be activated. For example, sub-vertical faults in the ranges, 70-115° or 165-200°, or more shallow dipping faults that trend around a northeast-southwest direction.

Changes in shear wave splitting before the 2010 Eyjafjallajokull eruption in Iceland.

Liu, S., Crampin, S., Luckett, R. and Yang, J., 2014.

We use shear wave splitting (SWS) above microearthquakes to monitor stress variations before the 2010 March and April flank and summit eruptions of Eyjafjallajökull volcano in Iceland. SWS time delays before Eyjafjallajökull show characteristic variations similar to those seen before earthquakes. The time delays display a nearly linear increase before the eruption, an abrupt change of slope and a rapid nearly linear decrease until the flank eruption begins. Similar variations before earthquakes are interpreted as stress-accumulation increases, and stress-relaxation decreases as microcracks coalesce onto the eventual fault plane. The changes in SWS before Eyjafjallajökull are interpreted as a similar stress-accumulation increase, as magma penetrates the crust, and stress-relaxation decrease as microcracks coalesce onto the magma conduit prior to magma release. We suggest that the remarkable similarity between stress changes before eruption and earthquake is strong evidence for the New Geophysics of a critically microcracked crust.

UK seismic hazard assessments for strategic facilities: a short history.

Musson, R.M.W., 2014.

The UK is a country with only low to moderate seismicity, and the long intervals between significant earthquakes in Britain results in people forgetting they occur. As a result, seismic hazard was only thought of for the first time in Britain in 1976. For ordinary construction, it is true that seismic hazard can be considered insignificant in the UK, but for strategic facilities, especially those with a high consequence of failure, such as nuclear power plants (NPPs), seismic hazard is important. This paper traces the history of such studies, with emphasis on those for the nuclear industry. The UK seismological community saw major investment from the nuclear industry after 1980. There was a cessation of NPP construction in Britain after 1995, but in recent years steps have been taken towards a resumption of NPP building, which will see a need for new seismic hazard studies.

The seismicity of Ghana.

Musson, R.M.W., 2014.

Although West Africa is generally an area of very low seismicity, an exception is a concentration of activity in Southern Ghana, especially near to the capital, Accra, which was heavily damaged by earthquakes in 1862 and 1939. Modern instrumental seismicity is poorly understood due to the limitations of seismic monitoring in the country. In this study, all available data are brought together to provide an earthquake catalogue for Ghana, and a new interpretation of the data for the 1862 earthquake is made. It is tentatively suggested that much of the recorded seismicity around Accra is in fact a very protracted aftershock sequence of the 1862 event.

Updated intensity attenuation for the UK.

Musson, R.M.W.. 2013

For many purposes, including seismic hazard and risk calculations, it is useful to be able to estimate the expected intensity value at a place as a function of magnitude and distance. Such a model was published by Musson (2005), relating intensity to local magnitude and hypocentral distance, based on a dataset comprising 727 isoseismals from 326 British earthquakes, including both modern and historical events, up to 1 October 2002, though for the preferred equation only a subset of this dataset was used. This update adds more data from earthquakes that have occurred since then, up to 1 June 2013. More importantly, the model is recast in terms of moment magnitude. The preferred result is $I = 3.50 + 1.28\ Mw – 1.18 \ln R$ This is derived from a subset of the total dataset, discarding data for intensity 2 (poorly constrained) and using only earthquakes with at least two isoseismals.

A history of British seismology.

Musson, R.M.W.. 2013.

The work of John Milne, the centenary of whose death is marked in 2013, has had a large impact in the development in global seismology. On his return from Japan to England in 1895, he established for the first time a global earthquake recording network, centred on his observatory at Shide, Isle of Wight. His composite bulletins, the “Shide Circulars” developed, in the twentieth century, into the world earthquake bulletins of the International Seismological Summary and eventually the International Seismological Centre, which continues to publish the definitive earthquake parameters of world earthquakes on a monthly basis. In fact, seismology has a long tradition in Britain, stretching back to early investigations by members of the Royal Society after 1660. Investigations in Scotland in the early 1840s led to a number of firsts, including the first network of instruments, the first seismic bulletin, and indeed, the first use of the word “seismometer”, from which words like “seismology” are a back-formation. This paper will present a chronological survey of the development of seismology in the British Isles, from the first written observations of local earthquakes in the seventh century, and the first theoretical writing on earthquakes in the twelfth century, up to the monitoring of earthquakes in Britain in the present day.

Rayleigh wave tomography of the British Isles from ambient seismic noise.

Nicolson, H., Curtis, A. and Baptie, B., 2014.

Traditional methods of imaging the Earth's subsurface using seismic waves require an identifiable, impulsive source of seismic energy, for example an earthquake or explosive source. Naturally occurring, ambient seismic waves form an ever-present source of energy that is conventionally regarded as unusable since it is not impulsive. As such it is generally removed from seismic data and subsequent analysis. A new method known as seismic interferometry can be used to extract useful information about the Earth's subsurface from the ambient noise wavefield. Consequently, seismic interferometry is an important new tool for exploring areas which are otherwise seismically quiescent, such as the British Isles in which there are relatively few strong earthquakes. One of the possible applications of seismic interferometry is ambient noise tomography (ANT). ANT is a way of using interferometry to image subsurface seismic velocity variations using seismic (surface) waves extracted from the background ambient vibrations of the Earth. To date, ANT has been used successfully to image the Earth's crust and upper-mantle on regional and continental scales in many locations and has the power to resolve major geological features such as sedimentary basins and igneous and metamorphic cores. Here we provide a review of seismic interferometry and ANT, and show that the seismic interferometry method works well within the British Isles. We illustrate the usefulness of the method in seismically quiescent areas by presenting the first surface wave group velocity maps of the Scottish Highlands using only ambient seismic noise. These maps show low velocity anomalies in sedimentary basins such as the Moray Firth, and high velocity anomalies in igneous and metamorphic centres such as the Lewisian complex. They also suggest that the Moho shallows from south to north across Scotland which agrees with previous geophysical studies in the region.

A local magnitude scale ML for the United Kingdom.

Ottemoller, L. and Sargeant, S., 2013.

We have developed a new local magnitude scale ML for the United Kingdom (UK) to replace the Hutton and Boore (1987) scale developed for southern California, which has been used in the UK until now. The new UK scale is developed from 1482 observations of 85 earthquakes on 50 stations located across the British Isles and Ireland. Most of the observations are from epicentral distances of less than 600 km and only few from greater distances up to 900 km. The distance range of the scale is, therefore, 0–600 km. The amplitude observations were used to invert for the parameters defining distance dependence in the ML scale and station corrections. Synthetic tests showed that the inversion was robust. The new ML scale for the UK is given by $ML=\log A+0.95\log R+0.00183R-1.76$, in which A is horizontal-component ground displacement amplitude in nanometers. The amplitudes are measured on traces that are filtered to simulate the Wood–Anderson seismograph. R is the hypocentral distance (in km). The UK scale is intermediate between scales determined for California and those of other intraplate areas such as Norway or the northeastern United States. The absolute station corrections found are all less than 0.5. The scale derived for the UK helps to reduce the overall variance of the mean magnitude estimates by 30%. Much of this improvement is due to the use of station corrections. Applying the UK scale to the database of recorded earthquakes results in a reduction of magnitude for earthquakes above ML 2 and a slight increase in magnitude for earthquakes below ML 2. The biggest change to the ML computation is likely to be for small earthquakes with few amplitude readings, where the use of station corrections makes a significant difference.

The value of multiple earthquake missions: the EEFIT L'Aquila Earthquake experience.

Rossetto, T., D'Ayala, D., Gori, F., Persio, R., Han, J., Novelli, V., Wilkinson, S.M., Alexander, D., Hill, M., Stephens, S., Kontoe, S., Elia, G., Verrucci, E., Vicini, A., Shelley, W. and Foulser-Piggott, R., 2014

In November 2012 EEFIT launched its first ever return mission to an earthquake affected site. The L'Aquila Earthquake site was chosen as this is a recent European event of interest to the UK and European earthquake engineering community. The main aims of this return mission were to document the earthquake recovery process and this paper presents an overview of the post-disaster emergency phase and transition to reconstruction in the Aquila area after the earthquake. It takes an earthquake engineering perspective, highlighting areas mainly of interest to the fields of structural/seismic engineering and reconstruction management. Within the paper, reference is made to published literature, but also to data collected in the field during the return mission that would not otherwise have been available. The paper presents some specific observations and lessons learned from the L'Aquila return mission. However, in light of current international efforts in conducting return missions, the paper ends with some reflections on the value that return missions can provide to the field of earthquake engineering in general, based on the EEFIT L'Aquila experience.

The SHARE European Earthquake Catalogue (SHEEC) 1000–1899.

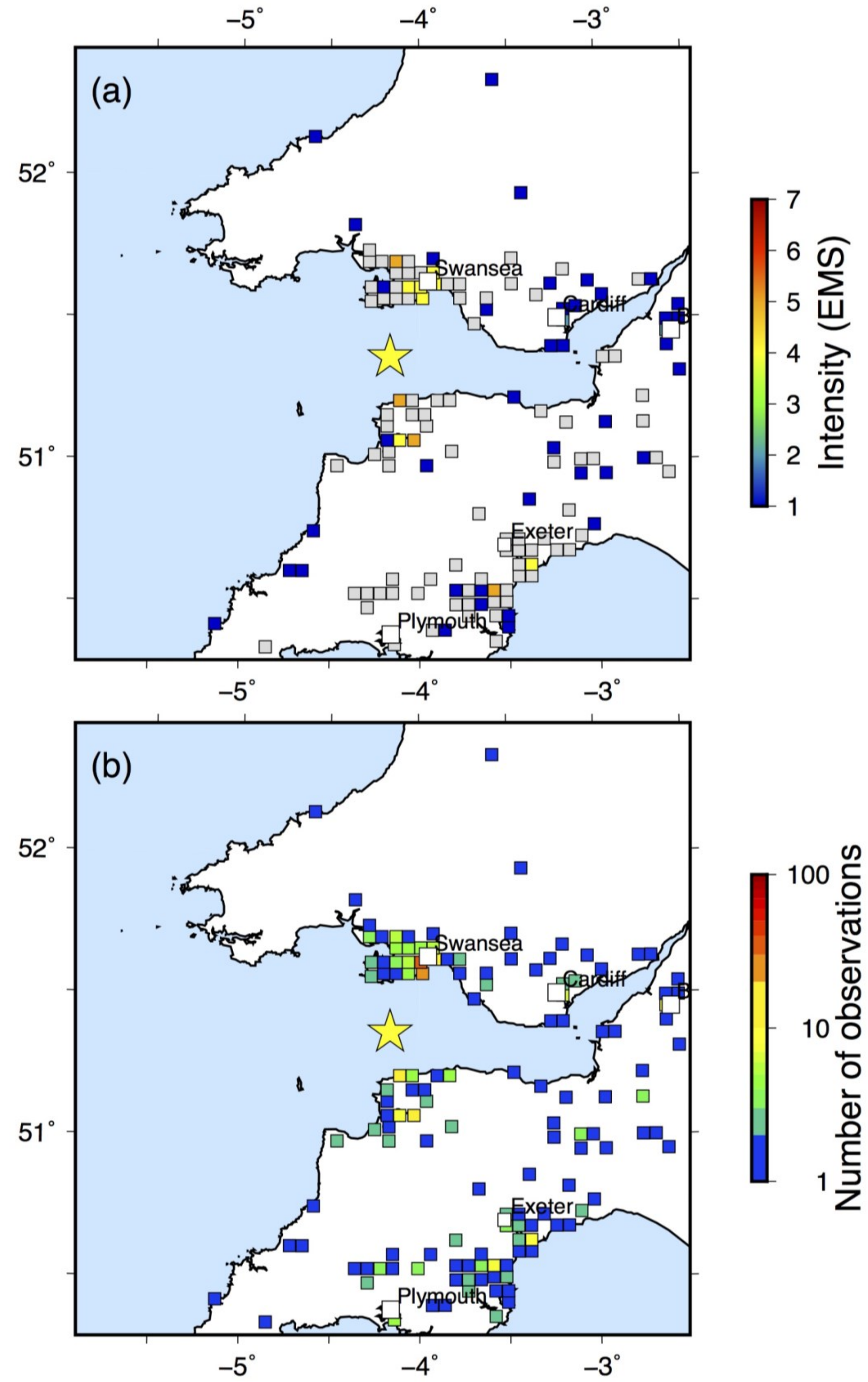
Stucchi, M., Rovida, A., Gomez Capera, A.A., Alexandre, P., Camelbeeck, T., Demircioglu, M.B., Gasperini, P., Kouskouna, V., Musson, R.M.W., Radulian, M., Sesetyan, K., Vilanova, S., Baumont, D., Bungum, H., Fäh, D., Lenhardt, W., Makropoulos, K., Martinez Solares, J. M., Scotti, O., Živčić, M., Albini, P., Batllo, J., Papaioannou, C., Tatevossian, R., Locati, M., Meletti, C., Viganò, D. and Giardini, D., 2013.

In the frame of the European Commission project "Seismic Hazard Harmonization in Europe" (SHARE), aiming at harmonizing seismic hazard at a European scale, the compilation of a homogeneous, European parametric earthquake catalogue was planned. The goal was to be achieved by considering the most updated historical dataset and assessing homogenous magnitudes, with support from several institutions. This paper describes the SHARE European Earthquake Catalogue (SHEEC), which covers the time window 1000–1899. It strongly relies on the experience of the European Commission project "Network of Research Infrastructures for European Seismology" (NERIES), a module of which was dedicated to create the European "Archive of Historical Earthquake Data" (AHEAD) and to establish methodologies to homogenously derive earthquake parameters from macroseismic data. AHEAD has supplied the final earthquake list, obtained after sorting duplications out and eliminating many fake events; in addition, it supplied the most updated historical dataset. Macroseismic data points (MDPs) provided by AHEAD have been processed with updated, repeatable procedures, regionally calibrated against a set of recent, instrumental earthquakes, to obtain earthquake parameters. From the same data, a set of epicentral intensity-to-magnitude relations has been derived,with the aimof providing another set of homogeneous Mw estimates. Then, a strategy focussed on maximizing the homogeneity of the final epicentral location and Mw, has been adopted. Special care has been devoted also to supply location and Mw uncertainty. The paper focuses on the procedure adopted for the compilation of SHEEC and briefly comments on the achieved results.

The English Channel 'tsunami' of 27 June 2011 : a probable meteorological source.

Tappin, D. R., Sibley, A., Horsburgh, K., Daubord, C., Cox, D. and Long, D., 2013

On 27 June 2011 a tsunami struck the Yealm Estuary, near Plymouth, and anomalous tides were experienced from Portugal to the Straits of Dover. These events were caused by a meteotsunami driven by convective cells extending from the Bay of Biscay into the English Channel. This paper explains meteotsunamis, their causes, previous occurrences and, finally, what happened on this day.



(a) Macroseismic intensities calculated for the magnitude 4.1 ML Bristol Channel earthquake on 20 February 2014. 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.