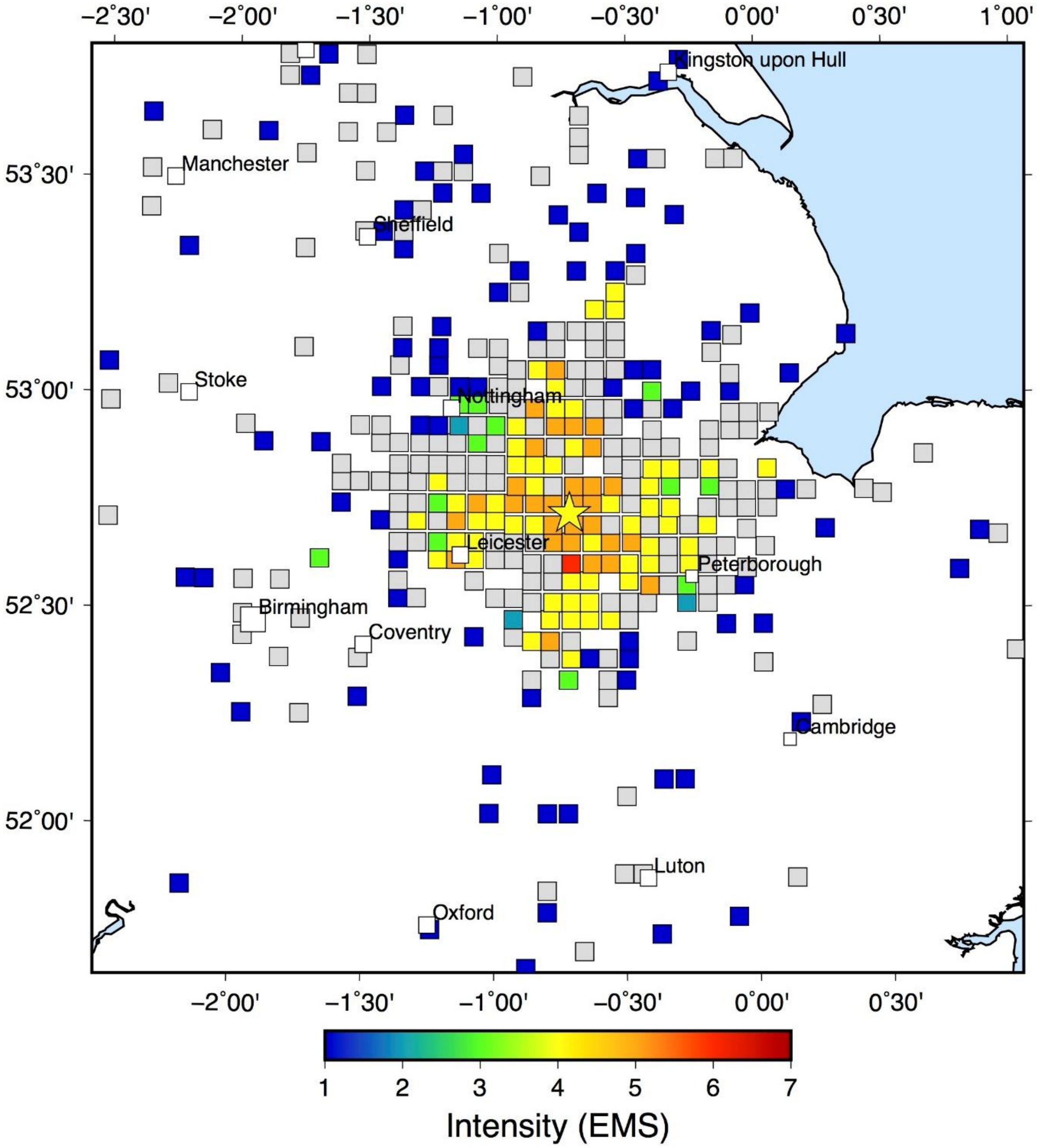
British
Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Earthquake Monitoring 2014/2015

BGS Seismic Monitoring and Information Service

Twenty-sixth Annual Report



BRITISH GEOLOGICAL SURVEY

OPEN REPORT OR/18/001

UK Earthquake Monitoring 2014/2015

R. Luckett (editor)

Key words

Monitoring, Earthquakes, Seismology.

Front cover

Macroseismic intensities calculated for the magnitude 3.8 ML Oakham earthquake on 28 January 2015.

Bibliographical reference

LUCKETT, R., 2018. UK Earthquake Monitoring 2014/2015. *British Geological Survey* Open *Report*, OR/18/001

36pp.

Edinburgh British Geological Survey 2018

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Summary

The British Geological Survey (BGS) operates a network of seismometers throughout the UK in order to acquire seismic data on a long-term basis. The aims of the Seismic Monitoring and Information Service are to develop and maintain a national database of seismic activity in the UK for use in seismic hazard assessment, and to provide 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 26th year of the project, one new broadband seismograph station was established, giving a total of 43 broadband stations. A new strong motion accelerometer was also installed. 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, 2015).

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

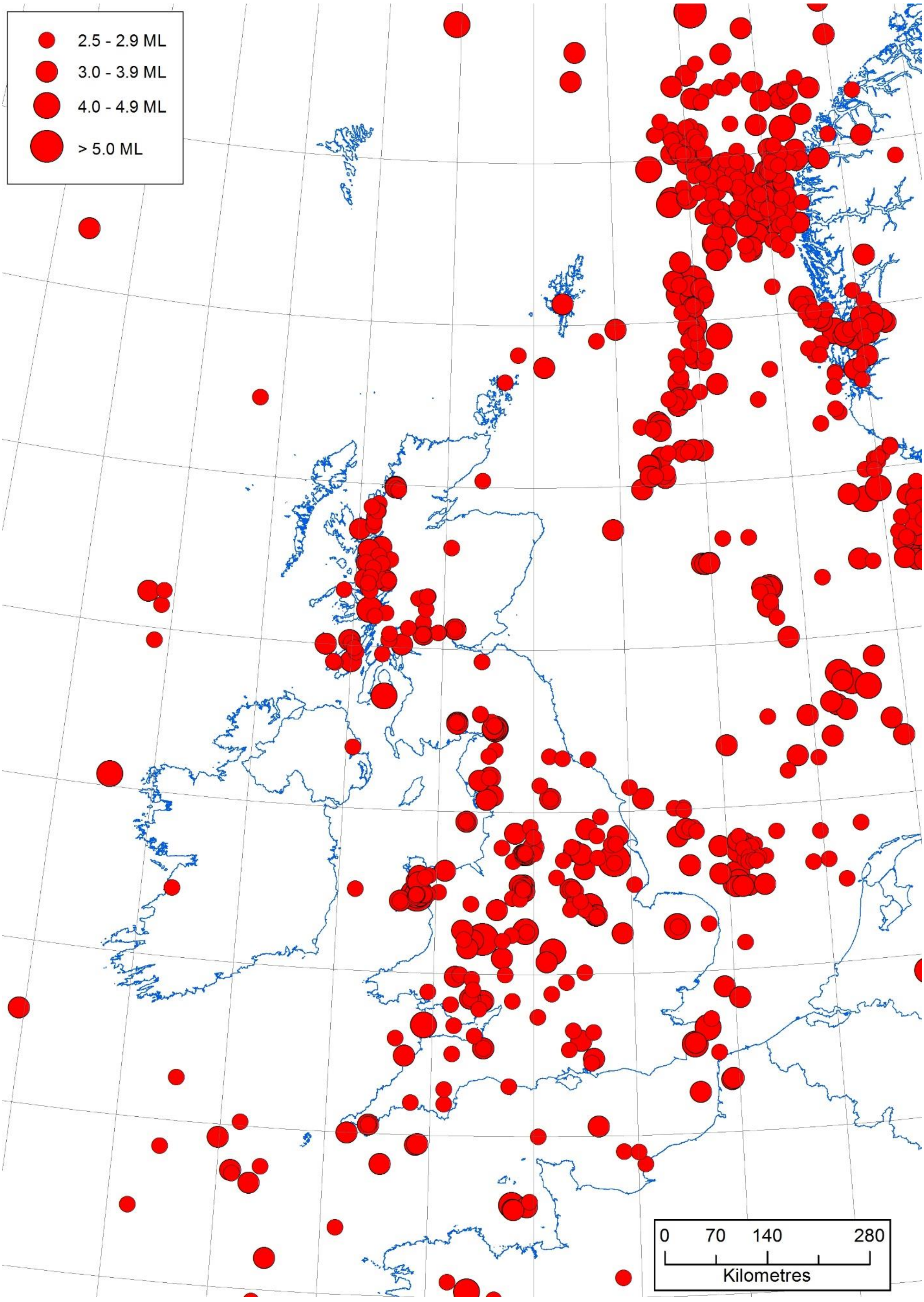
Introduction

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 the various sources and causes of seismic events that 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 2015.

Introduction

Monitoring Network

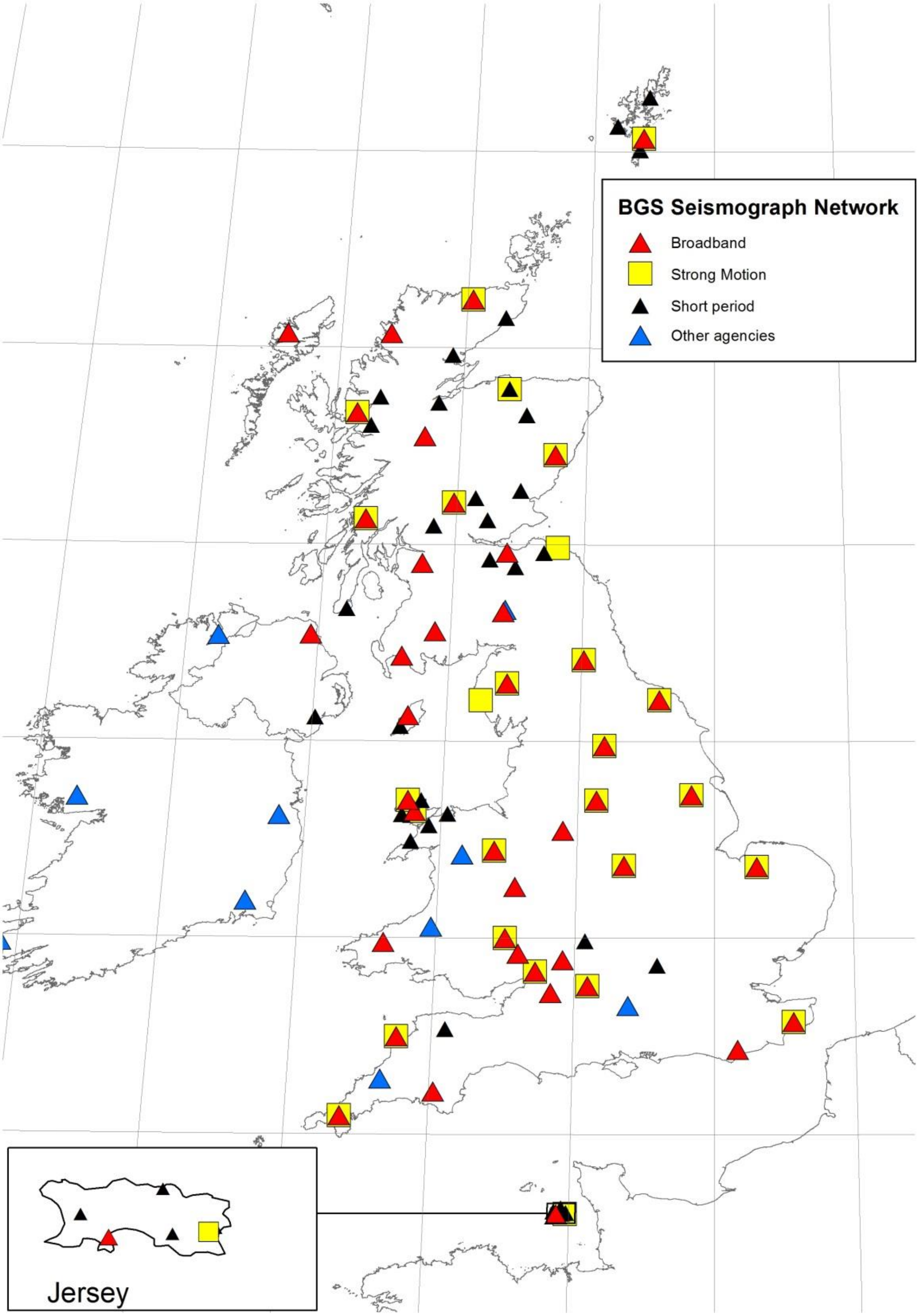
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late 1990s, the number of stations reached its peak of 146, with an average spacing of 70 km. The installation of broadband seismometers in the period from 2005 to present is providing 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 43 broadband sensors at stations across the UK along with 29 strong motion accelerometers with even higher dynamic range for recording very large signals.



BGS seismograph stations, March 2015

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.

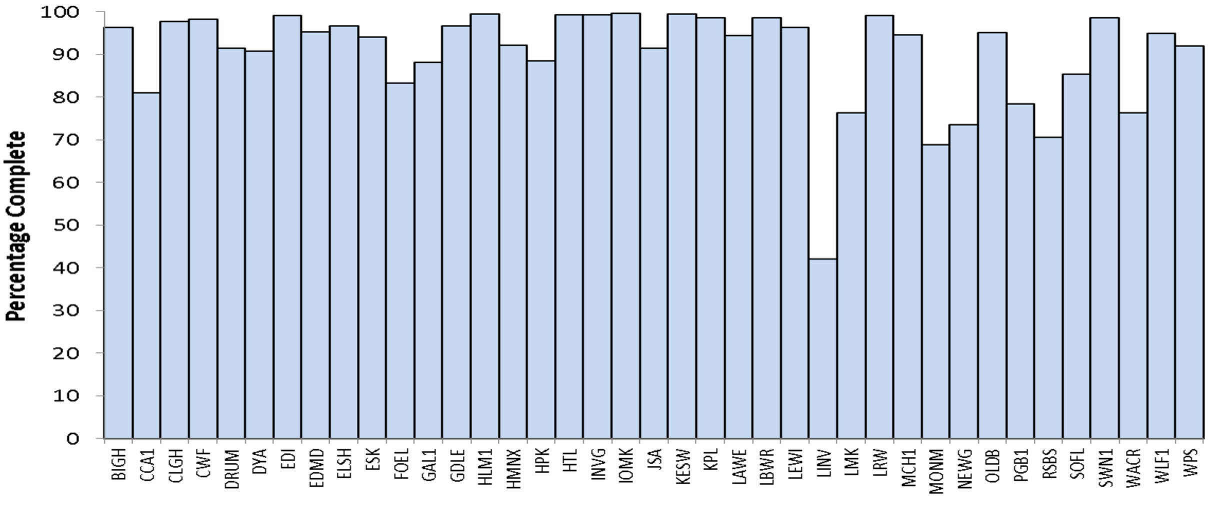
In the last year, one new broadband station was installed at Lochinver in northwest Scotland. This takes the total number of broadband stations operated by BGS to 43. Continuous data from all broadband stations are transmitted in real-time to Edinburgh, where they are analysed and archived.

There are now 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.

The two accelerometers at Torness power station near Edinburgh were replaced with modern equipment and are now being telemetered and acquired centrally in real-time. A strong motion sensor was also installed at Charnwood Forest, Leicestershire, in addition to the broadband sensor there. There are now 29 strong motion sites that ensure we will have on-scale data regardless of where a larger earthquake occurs.

During the year, a total of 75 field trips were made to visit stations around the UK. Of these visits, 67 were for maintenance or fault repair, four were to carry out site surveys for new stations and four were for installation of new stations. No stations were decommissioned this year.

Continuous data from all our stations are stored online at BGS. The completeness of these data can be easily checked to gain an accurate picture of network



Data completeness for all broadband stations that operated throughout 2014-2015. Data are more than 90% complete for more than 75% of stations. LINV was installed part way through the year.

performance. For 2014/2015 data are more than 90% complete for more than 75% of stations. Data losses result from failure of outstation hardware, communications problems, or failure of central data processing. The data acquisition is able to recover from short breaks in communications links to outstations by re-requesting missing packets of data from local data buffers, but failure of outstation hardware requires intervention by local operators or maintenance visits.

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 of events in a number of areas.

View from the BGS monitoring seismic monitoring station at Lochinver.

Achievements

Information Dissemination

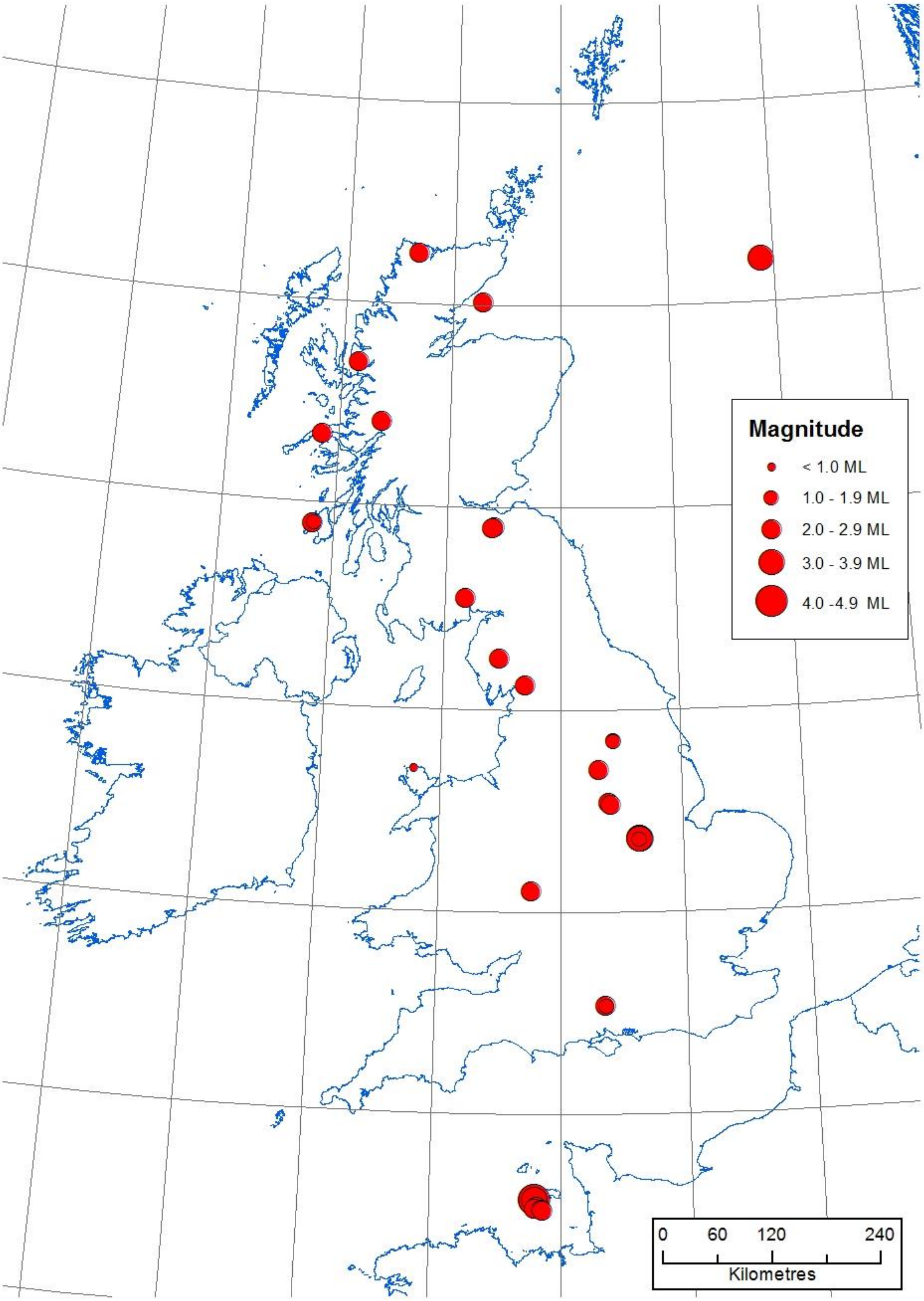
It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received notification by e-mail whenever an event was felt or heard by more than two individuals.

Notifications were issued for 36 UK events within the reporting period – two of which were sonic booms rather than earthquakes. 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, nine enquiries were received from Nuclear Power Stations after alarms were triggered. In each case, a response was provided within 15 minutes.

This year the webserver for the Seismology web pages was upgraded, allowing many more simultaneous visits. These web pages are directly linked to our earthquake database to provide near real-time lists of all 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. It 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. Over 2,000 questionnaires were collected for the Oakham earthquake on 28 January 2015 (3.8 ML).

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.

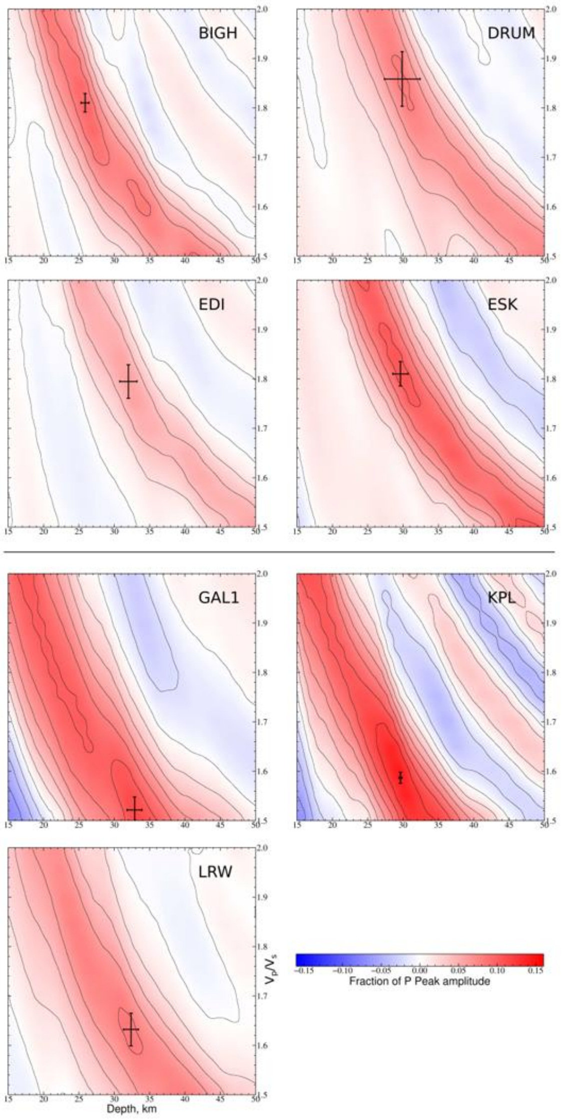


Events in the reporting period (1 April 2014 to 31 March 2015) for which alerts have been issued. Circles are scaled by magnitude**.**

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.



Stacked H-k plots for 7 stations in Scotland. The crosses show (with error bars of 1 standard deviation) the maximum P reflection plotted against depth to Moho and Vp/Vs ratio.

A student at Cambridge University, funded partly by the BGS is calculating receiver functions for BGS stations in Scotland as part of an effort to map the Moho. This is part of research into the causes of regional uplift in the British Isles. Thinner crust beneath northwest Scotland may suggest that present-day topography is maintained by regional dynamic support, originating beneath the lithosphere.

BGS are co-investigators in the Earthquakes Without Frontiers (EWF) consortium led by the University of Cambridge that won funding in the NERC ‘Improving Resilience to Natural Hazards’ call. The project started in 2012. BGS seismologists are contributing to research relating to ground motion modelling and seismic hazard assessment, and to the wider trans-disciplinary process.

In September 2014 and February 2015, Susanne Sargeant and Brian Baptie visited Kazakhstan to work with the Kazakh Institute of Seismology. The work included a training course on seismic data analysis and development of research on attenuation of seismic waves and determination of moment magnitudes for earthquake in the region. The work is part of the EWF project.

Susanne Sargeant is continuing her research as a NERC Knowledge Exchange Fellow, working on “Use of science in decision-making for disaster risk reduction”.

Richard Luckett visited Ethiopia in December 2014 as part of the NERC funded RiftVolc project to research past and current volcanism and volcanic hazards in the Main Ethiopian Rift. The five year long project started in September 2014 and includes the universities of Edinburgh, Bristol, Cambridge, Leeds, Oxford and Southampton as well as Addis Ababa University and the Geological Survey of Ethiopia. He worked with the Institute of Geophysics, Space Science and Astronomy (IGSSA), the local agency, to improve their seismic acquisition and to find suitable sites for stations to be installed by the consortium. These sites will be telemetered in real-time to Addis Ababa and contribute to the impact deliverables of RiftVolc[1].

A joint project between the University of Aberdeen (N. Rawlinson), the University of Edinburgh (A. Curtis) and the British Geological Survey (B. Baptie), entitled “Ambient seismic noise and the North Sea: Can we image what lies beneath?” has received a Carnegie Collaborative Grant. The goal of this project is to investigate whether ambient noise data collected by permanent seismic stations located in countries surrounding the North Sea is capable of imaging the geology beneath the North Sea. The improved models will allow more accurate location of earthquakes and improve upon prior estimates of magnitudes and focal mechanisms.

BGS have begun to deploy stations across the north of England as part of UKArray, a joint project between BGS, Edinburgh University, Bristol University, Liverpool University and Leicester University. The project has two main aims: to answer fundamental scientific questions about the earth beneath the UK, and to address issues relating to the future use of the sub-surface, both as a source for sustainable energy and as a means of energy and waste storage. So far, five stations have been deployed and are transmitting near real-time data.

BGS 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). 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. BGS also exchanges data in near real-time with a number of European partner agencies, including Ireland, France, Norway, Denmark and the Netherlands. These data are incorporated into our automatic data processing to improve detection capability in offshore areas.

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[1] https://www.riftvolc.geos.ed.ac.uk/

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 public as quickly as possible Earthquake lists, maps and specific pages are generated and updated automatically whenever a new event is entered in our database or when the parameters for an existing event are modified. We continue to provide displays of real-time data from most of our seismic stations, which allows 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 1,833,700 visitors logged in the year. Significant peaks were observed following the Oakham earthquakes (April 2014 and January 2015), the Jersey earthquakes (July 2014) and the Winchester earthquake (January 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 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.

In October 2014, Paul Denton and John Stevenson (BGS), delivered teacher training workshops in Sion, Switzerland, as part of NERA, an EU project to integrate key research infrastructures in Europe for monitoring earthquakes and assessing their hazard and risk. The workshops brought together scientists, civil engineers, civil protection officers and teachers from around Europe and the Middle East[2].

Paul Denton from BGS was interviewed by the BBC along with pupils from Catmose College in Rutland, following the

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[2] http://www.sera-eu.org/en/home/

magnitude 3.8 ML Oakham earthquake on 28 January 2015. The earthquake was recorded by a school seismometer at the college.

The demolition of a Leicester City Council office block on 23 February 2015 was recorded by seismometers in a number of nearby 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 2014-2015, at least 892 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.

Replaying earthquake recordings at a BGS open day.

Seismic Activity

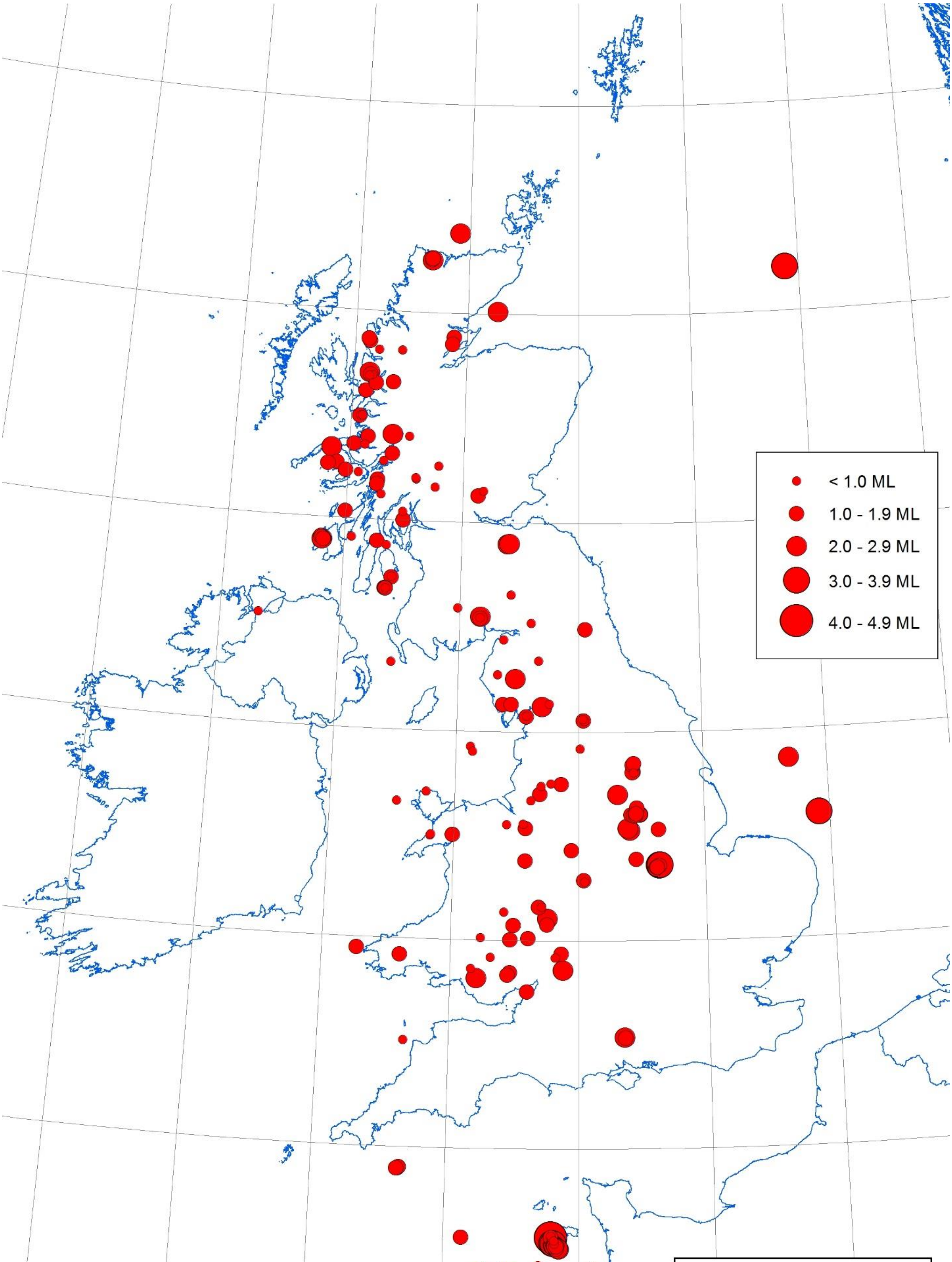
The details of all earthquakes, felt explosions and sonic booms detected by the BGS seismic network have been published in monthly bulletins and compiled in the BGS Annual Bulletin for 2014, published and distributed in Galloway (2015).

There were 342 local earthquakes located by the monitoring network during 2014-2015, with 36 having magnitudes of 2.0 ML or greater, and eight having magnitudes of 3.0 ML or greater. There were 54 felt earthquakes in 2014-2015, 25 of which had a magnitude of 2.0 ML or greater.

The largest earthquake in and around the British Isles during 2014-2015 was a magnitude 4.3 ML event near to Jersey. The earthquake occurred on 11 July 2014 at 11:54 UTC, with an epicentre approximately 15 km west of the island. The earthquake was widely felt in the Channel Islands and beyond, with a maximum observed intensity of 4 EMS. This earthquake had many aftershocks, including a magnitude 3.3 ML on 23 July and a magnitude 2.9 ML on 25 February 2015.

In April 2014, there were a series of earthquakes near Oakham, Rutland. The two largest were on 17 and 18 April and these had magnitudes of 3.2 ML and 3.5 ML, respectively. Both earthquakes were reported as felt by hundreds of people locally. The furthest felt reports were received from Tamworth, approximately 60 km to the west of the epicentre, and Gainsborough, approximately 75 km to the north of the epicentre. On 28 January 2015, a 3.8 ML earthquake occurred in the same vicinity. This time over 2,000 felt reports were received from up to 150 km away.

On 27 January 2015 at 18:30 UTC, there was an earthquake near the city of Winchester, Hampshire with a magnitude of 2.9 ML. Over 400 reports were received from members of the public, almost all of them coming from within a 10 km radius of the epicentre, covering Winchester and surrounding towns and villages. Over half the reports described the shaking strength of the earthquake to be moderate, and described the sound strength as moderate to loud. Over half the reports stated that windows rattled. An aftershock, with a magnitude of 1.8 ML, was recorded for this event at 16:25 UTC on 30 January. Felt reports were received from five members of the public living in close proximity to the epicentre.



Epicentres of all earthquakes in and around the UK detected in the reporting period (1 April 2014 – 31 March 2015).

Seismic Activity

The Oakham Earthquakes

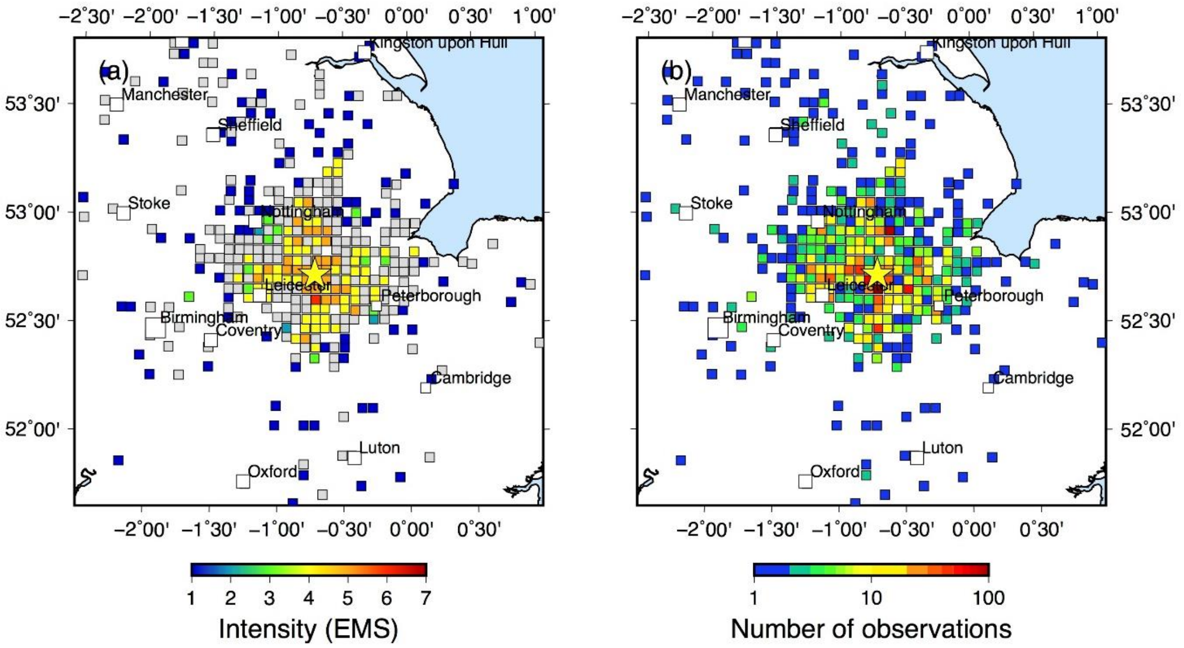
In April 2014 there was a series of earthquakes near Oakham, Rutland. The two largest were on 17 and 18 April and had magnitudes of 3.2 ML and 3.5 ML, respectively. These were followed by a 3.8 ML earthquake in the same location on 28 January 2015.

A magnitude 3.2 ML earthquake occurred on 17 April 2014 at 06:07 UTC, approximately 5 km ESE of Oakham, Rutland, and 11 km SSE of Melton Mowbray, Leicestershire. This was the largest earthquake to have occurred in the area since the magnitude 4.1 ML Melton Mowbray earthquake of 28 October 2001.

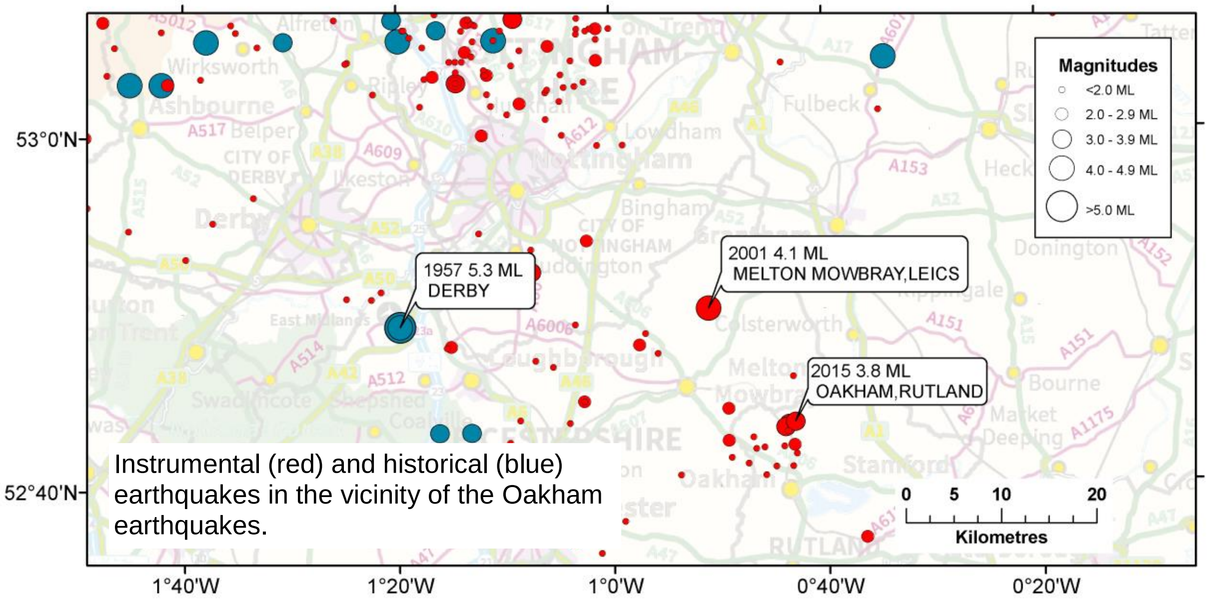
Almost 24 hours later, at 06:50 UTC on 18 April 2014, a magnitude 3.5 ML earthquake occurred in the same vicinity.

The earthquakes were widely felt across the East Midlands of England and BGS collated 638 reports from the earthquake on 17 April and 749 reports for the earthquake on 18 April. These data were used to calculate macroseismic intensities across the affected region. Most of the reports were within a 30 km radius of the epicentre, with most people describing the shaking strength of the earthquake as either weak or moderate. Around half the reports stated that windows rattled and a few mentioned crockery rattling and furniture shaking. Both earthquakes were assigned a maximum intensity of 4 EMS.

On 28 January 2015, a magnitude 3.8 ML earthquake occurred, again with a similar location. Over 2,000 reports were received and it was felt over a slightly larger area, with reports from as far as Ripon (150 km north) and Luton and Telford (125 km



(a) Macroseismic intensities for the Oakham earthquake on 28 January 2015. Intensities are calculated in 5 km grid squares and a minimum of five observations are required to calculate an intensity value. Squares are coloured by intensity. The grey squares show places where the earthquake was felt but there were fewer than five observations. (b) The number of observations in each grid square.

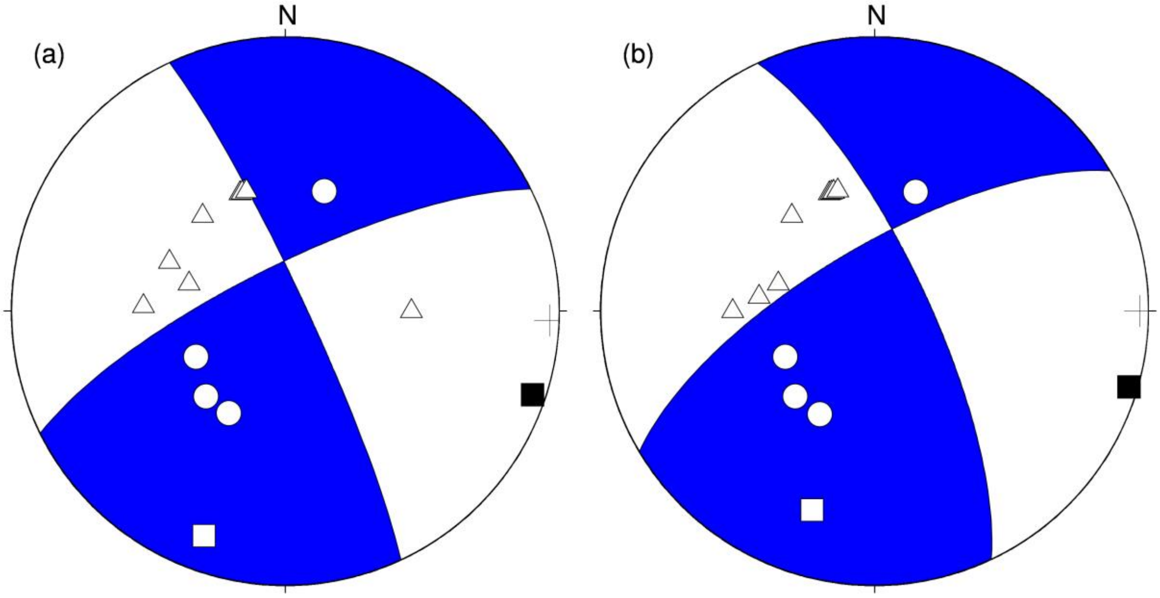


Instrumental (red) and historical (blue) earthquakes in the vicinity of the Oakham earthquakes.

south and east, respectively). Over 250 people reported having been awoken by the event and 700 said they were frightened. The maximum intensity was 4 EMS.

This part of England has experienced some notable earthquakes in the past. For example, a magnitude 5.3 ML earthquake southeast of Derby in 1957 was one of the most damaging British earthquakes of the 20th Century, causing widespread damage to chimneys and roofs in and around Derby, Nottingham and Loughborough. The epicentre was approximately 40 km west of the Oakham earthquakes, near Castle Donnington. More recently, a magnitude 4.1 ML earthquake near Melton Mowbray on 28 October 2001 was approximately 15 km to the northwest of Oakham.

Focal mechanisms were calculated for the magnitude 3.5 ML earthquake on 18 April and the magnitude 3.8 ML earthquake on 28 January using the method of Hardebeck and Shearer (2003). Both mechanisms show strike slip faulting, with either right lateral slip on a steeply dipping fault that strikes approximately northeast-southwest, or left lateral slip on a steeply dipping fault that strikes approximately northwest-southeast.



Focal mechanisms calculated for the magnitude 3.5 ML earthquake on 18 April (a) and the magnitude 3.8 ML earthquake on 28 January (b). The former was calculated using 16 polarities and one SH/P amplitude ratio. The latter was calculated using 13 polarities and one SH/P amplitude ratio. The plots show lower hemisphere, equal area projections. The blue and white shaded areas show directions of compressional and dilatational first motions. The white circles and triangles show measured compressional and dilatational first motions, respectively. The black and white squares show the orientations of the axes of maximum (P) and minimum (T) compression, respectively.

Seismic Activity

The Jersey Earthquake

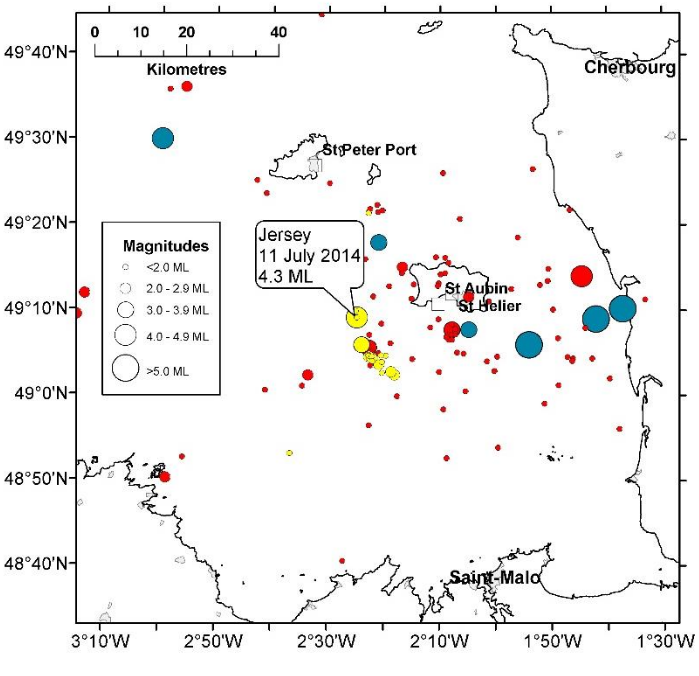
A magnitude 4.3 ML earthquake was recorded near Jersey on 11 July 2014. The earthquake was widely felt across the Channel Islands with a maximum observed intensity of 4 EMS.

The earthquake occurred at 11:54 UTC (12:54 BST) on 11 July 2014, with an epicentre approximately 15 km west of Jersey, Channel Islands. The instrumental magnitude was determined at 4.3 ML, and the earthquake was located approximately 37 km west of a magnitude 5.2 ML earthquake that occurred on 12 April 1933.

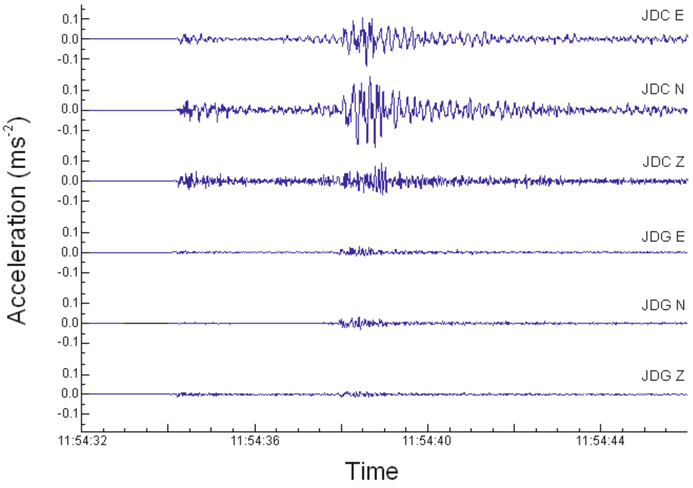
Over 140 members of the public completed our online macroseismic questionnaire, allowing EMS intensity to be calculated in different locations. A maximum intensity of 4 EMS was observed on Jersey.

Further afield, two felt reports were received from the south coast of England, one from Torquay, Devon, and the other from Poole, Dorset. The EMSC also received many felt reports from the Channel Islands and several felt reports from mainland France, around the coast of the Gulf of St Malo.

Most people described the shaking strength of the earthquake as moderate, with a trembling effect, and described the sound strength as faint to moderate. Almost all reports stated that windows rattled. Reports described, “I thought a plane had crashed nearby”, “everyone in the office noticed it and people in surrounding shops” and “sudden like a large impact, with a bang/rumble, enough to make you jump and go outside to see what happened”.



Yellow circles show the Jersey earthquake of 11 July 2014 and its aftershocks. Red and blue circles show instrumentally recorded and historical seismicity, respectively. Circles are scaled by magnitude.



Recorded ground accelerations at Queen’s Dam, Jersey, 27 km from the epicentre. JDC is at the crest of the dam, JDG is at the base. The peak ground acceleration of 0.2 ms^{-2} at the dam crest is five times greater than at the base.

Seismic Activity

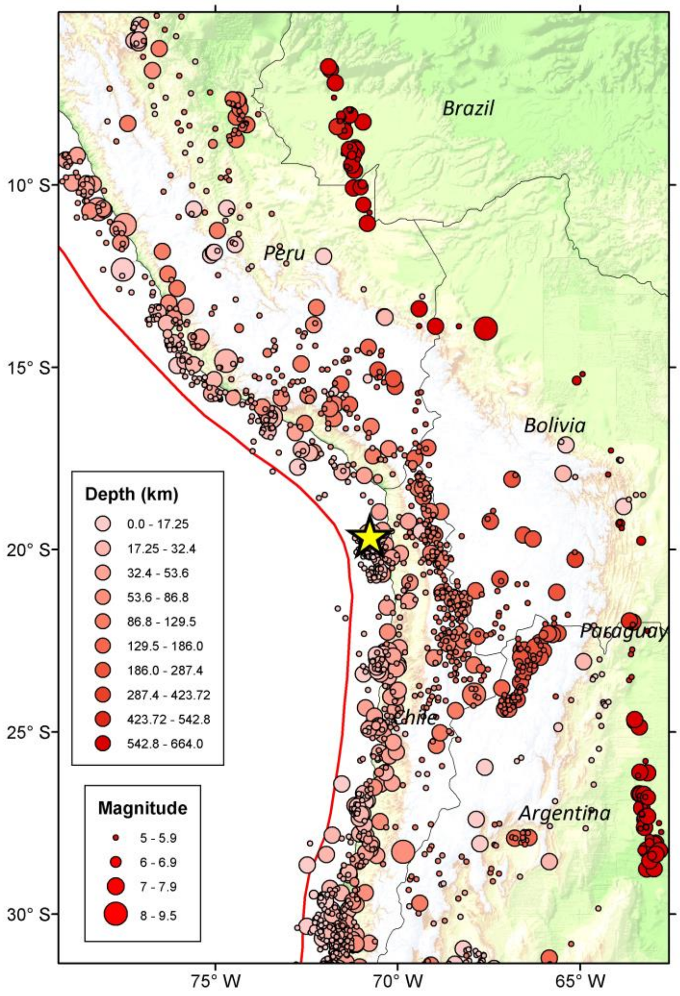
Overview of global earthquake activity

Worldwide, there were 15 earthquakes with magnitudes of 7.0 or greater. This number is in keeping with long term annual averages based on data since 1900, which suggests that, on average, there are 16 earthquakes with magnitude 7.0 or greater each year.

The largest earthquake of the year was the 8.2 Mw earthquake in northern Chile on 1 April 2014 at 23:46 UTC. This occurred offshore, 94km northwest of Iquique. It generated a tsunami over 2m high that hit the coast 20 minutes after the earthquake. The earthquake was felt all across Chile, as well as in Peru and Bolivia. The maximum intensity was 8 MMI in Iquique.

Calculated focal mechanisms show thrust faulting, which is consistent with slip on the primary plate boundary interface, where the Nazca plate subducts eastward beneath the South America plate. Some of the largest earthquakes in the world have occurred at this plate boundary, including the 2010 Maule earthquake (8.8 Mw) and the 1960 earthquake in southern Chile (9.5 Mw).

On 18 April 2014, a 7.2 Mw earthquake occurred near the Pacific coast of Mexico in the state of Guerrero. The depth and mechanism are consistent with slip at the plate boundary between the Cocos oceanic plate and the North American plate. The Cocos plate is subducting beneath the North American plate at a rate of approximately 65 mm/yr.



The April 1st 2014 Chile earthquake. The yellow star shows the location of the earthquake. The circles are scaled by magnitude and coloured depending on depth.

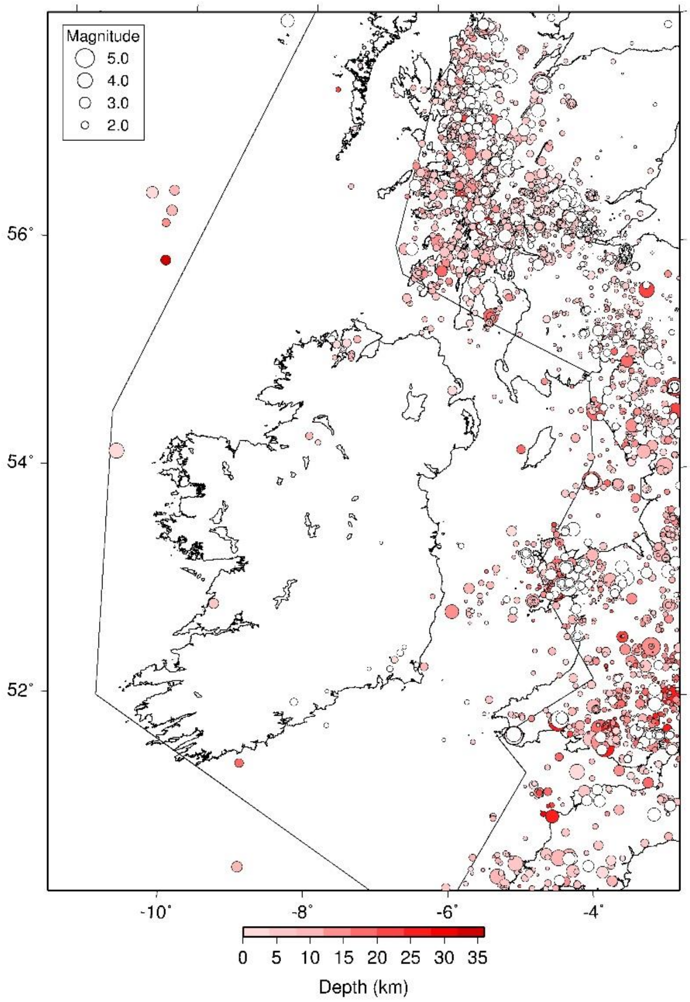
Scientific Objectives

The Remarkable Lack of Earthquakes in Ireland

Ireland is characterised by very low levels of seismic activity in comparison to Britain. Research commissioned by the Irish Environmental Protection Agency examined existing data on natural seismicity in Ireland and a combined historical and instrumental catalogue was used to determine earthquake activity rate.

The historical seismicity of Ireland has been studied by a number of researchers including Davison (1924) and Richardson (1975) and a review of published data confirms that earthquake activity is very low. Historical accounts reveal only 26 events in the period 1500 to 1970, which can be deemed credible. 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. All of these have low intensities suggesting that these were small earthquakes. Nearly all the historical activity is concentrated around the coast and there is an almost complete absence of seismicity inland.

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



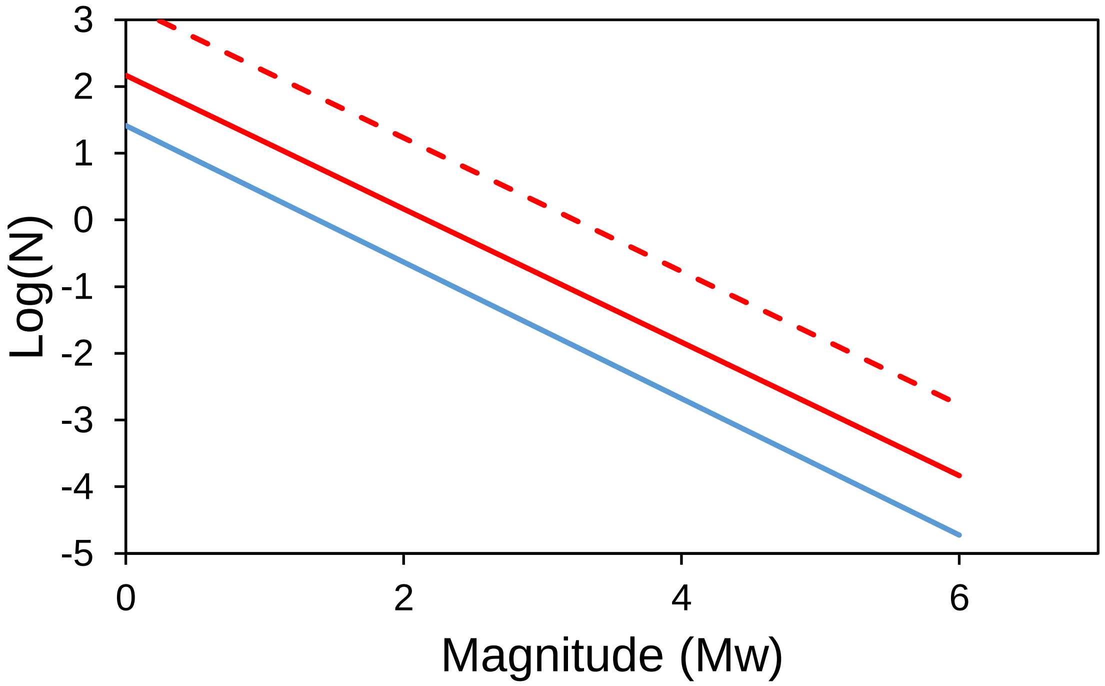
All historical and instrumental seismicity in and around Ireland from the BGS catalogue. Symbol size is proportional to magnitude and colour indicates depth, with lighter shades of pink denoting shallower events. Events of unknown depth are shaded white. The solid black line indicates the source zone used for Ireland.

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 in 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.

The combined historical and instrumental catalogue was used to determine an earthquake activity rate for Ireland, i.e. the number of earthquakes above a given magnitude in a given period of time. We estimate the activity rate, *a*, for the source zone model of Ireland from the SHARE project (Giardini et al, 2013) using a penalized maximum likelihood method (e.g Johnston et al., 1994).

Using the catalogue completeness used for offshore areas around Britain gives an activity rate, *a* = 2.1673. This suggests a magnitude 4 Mw earthquake approximately every 70 years, but this is significantly more earthquakes than are observed for Ireland. However, using the value for catalogue completeness usually used for onshore UK gives an activity rate, *a* = 1.4142. This suggests an earthquake with a magnitude of 4 Mw or greater approximately every 476 years, which agrees with the observed data better. This highlights the problem of estimating reliable rates in low seismicity regions, where data are sparse.

The absence of significant earthquakes in Ireland is real and not a result of lack of observations. This absence is difficult to explain, given the similarities in geology to the UK. A rate of *a* = 1.4142 (i.e. a magnitude of 4 Mw or greater approximately every 476 years) seems consistent with the observed earthquake data. This contrasts with a rate for the rest of the UK of a magnitude 4 Mw earthquake every six years.



Magnitude-frequency relationships for Ireland. The red line shows the best-fit values of *a*=2.1673 and *b*=1.00 using the catalogue completeness for offshore areas around the UK. The blue line shows the best-fit values of *a*=1.4142 and *b*=1.023 using the catalogue completeness for onshore UK. The red dashed lines shows the average values calculated for Britain of *a*=3.23 and *b* =1.

Scientific Objectives

Mining Induced Seismicity at Thoresby Colliery

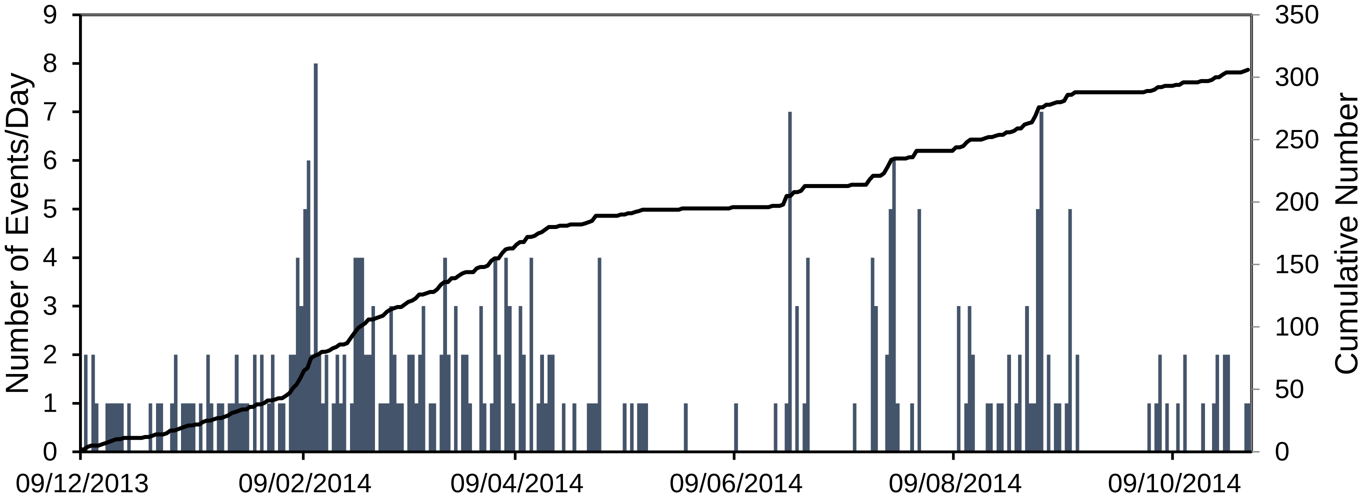
Between December 2013 and October 2014, over 300 small earthquakes were detected in and around New Ollerton, Nottinghamshire. Many of these were felt locally. This is an area with a history of seismic activity related to coal mining and the occurrence of these events coincided with the resumption of deep mining operations at the nearby Thoresby Colliery. A temporary network of seven seismometers was deployed to allow detailed analysis of these events.

Small to moderate earthquakes have been observed in the coalfields of Britain for at least the last hundred years. For example the Stafford earthquake of 1916 (Davison, 1919).

In December 2013, BGS began to record small earthquakes in the vicinity of New Ollerton, Nottinghamshire, an area with a history of seismic activity related to coal mining (Bishop et al., 1994). Many of the tremors were felt by local residents but there were no reports of any damage. Event locations determined using the regional seismic monitoring network broadly clustered to the north and west of New Ollerton, but with considerable scatter.

In February 2014, a local network of seven stations was installed around Thoresby Colliery, near the centre of the seismic activity. This improved location accuracy to 1-3 km and it became clear that the ongoing longwall mining at the colliery was the cause of the seismicity as the locations of the events corresponded to mining activity.

The clustering of initial locations suggested that the relative locations of the events could be improved using multiple event location techniques. The double difference location method (Waldhauser and Ellsworth, 2000) was used to determine

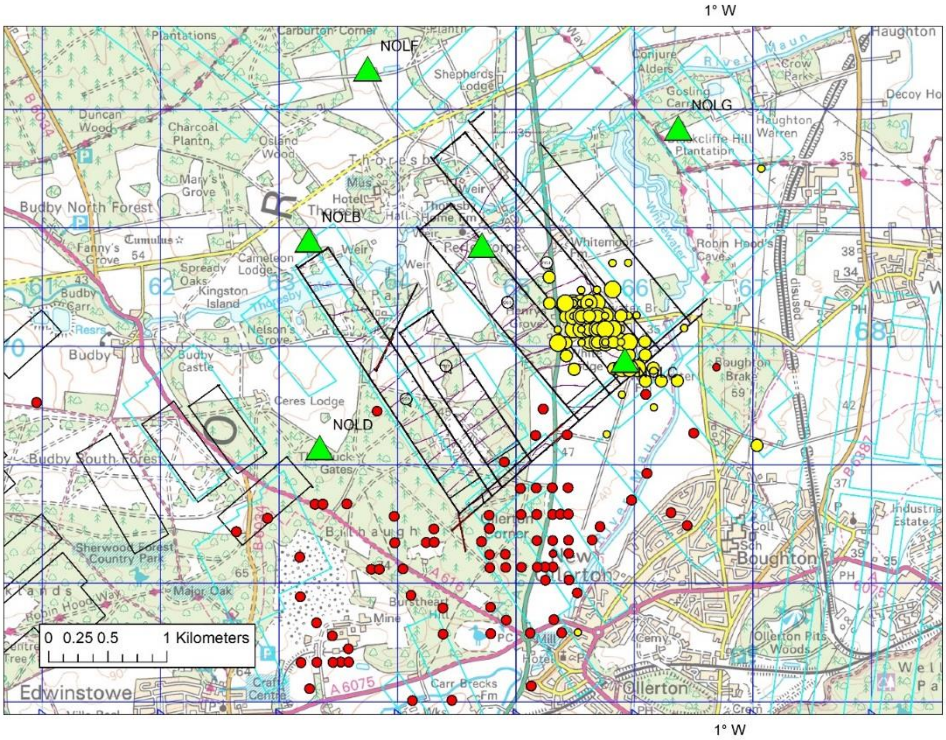


Number of events/day and the cumulative number of events as a function of time.

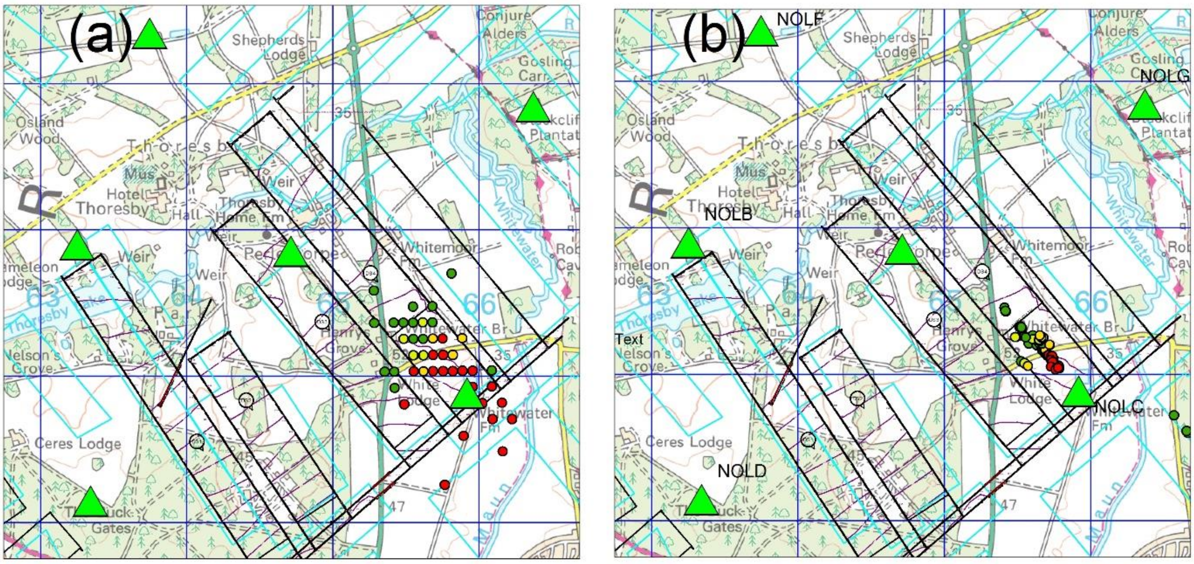
precise relative locations for earthquakes recorded by the temporary sensors.

This method minimises the difference between the travel time residuals of earthquake pairs and since the velocities along a path for neighbouring earthquakes recorded on one station are nearly identical, no station or source-specific corrections are required. Waveform cross-correlation (Schaff and Richards, 2004) was used to obtain precise relative travel time differences that were combined with the catalogue readings to obtain the relative locations.

The resulting relative event locations show a clear picture emerging of seismicity migrating along the coal seam corresponding to the mining activity as confirmed by the mine operators.



Location calculated for earthquakes at Thoresby Colliery. The red dots are the locations using the national network only. The yellow dots are the locations also using the local network shown by the green triangles. The black rectangles are the coal seams at 1 km depth.



Single event locations (a) and double difference locations (b). The events are coloured by time, green to red from February to May.

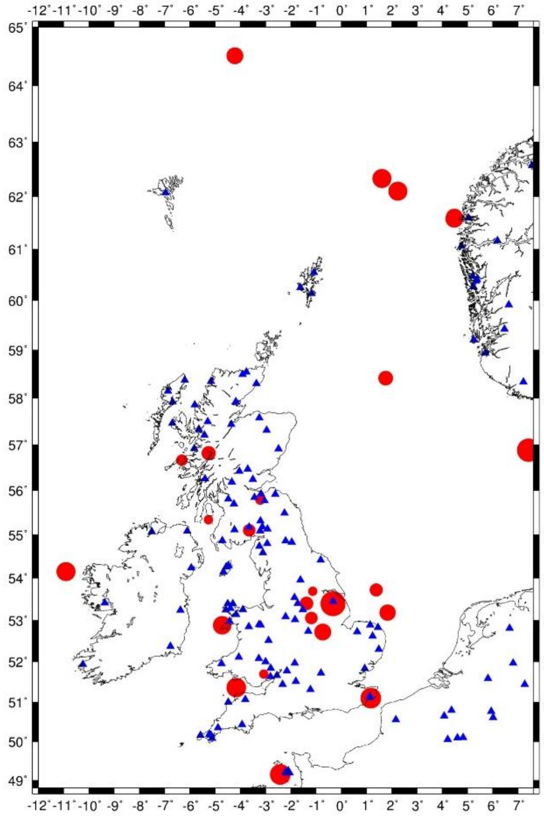
Scientific Objectives

Automatic Seismic Amplitude Measurement

Magnitude ratios, such as those between body-wave magnitude (m_b) and surface-wave magnitude (*Ms*) are commonly used to discriminate nuclear explosions from earthquake activity. The Atomic Weapons Establishment (AWE) commissioned BGS to develop software to automatically determine boy-wave amplitudes that can be used to obtain measurements for contructing a body-wave magnitude scale for the UK.

In the UK, the first attempt to relate event magnitude to explosion charge size using local recordings of quarry blasts and underwater explosions was carried out by Jacob and Neilson (1977). However, the sizes of seismic events in the UK are routinely estimated using a local magnitude scale that is based on the maximum amplitude (often *Lg*) within the seismic recording (e.g. Booth, 2007). This is not optimal for seismic studies of surface explosive sources because there is no adequate theoretical basis for the generation of S-waves from explosive sources. A magnitude scale, based on P-waves and tied to the global m_b scale, would allow us to constrain an m_b -to-yield relationship.

As a first step towards this goal, software was developed to automatically obtain a variety of amplitude measurements. These include maximum peak-trough amplitudes for a windowed P-arrival, filtered in different pass bands. The root-mean-square amplitude for these windows was also considered. The software is based on the SEISAN analysis package (Haskov and Ottemoller, 1999) used by the BGS and was designed to be as flexible as possible, so as to enable different methods to be tried. To test these methods a set of 29 earthquakes was selected that cover a range of magnitudes. For each magnitude, an earthquake was selected with the most stations for an earthquake of that size. The test data includes four earthquakes each from the magnitude bands 1.5 to 2, 2 to 2.5 and 2.5 to 3.5, five earthquakes each from 3 to 3.5 and 3.5 to 4 and six earthquakes



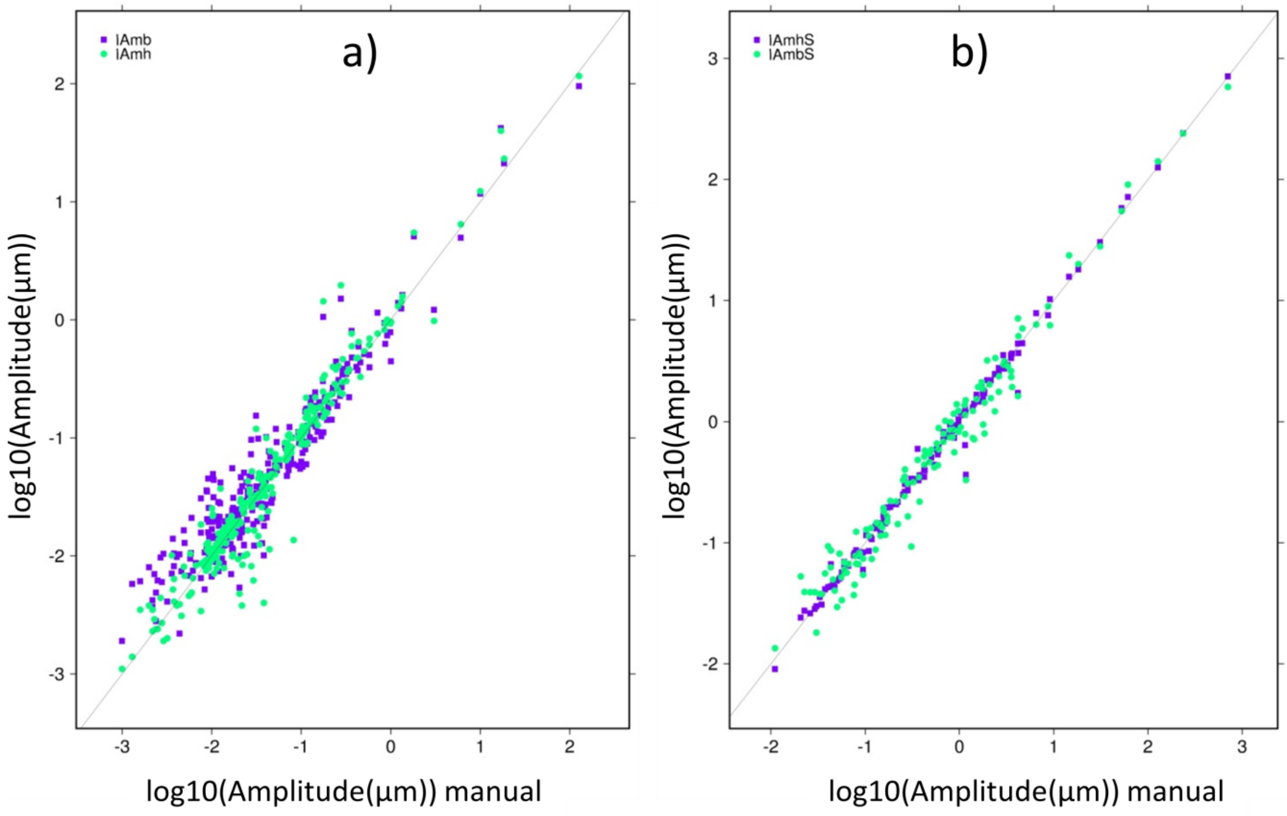
Earthquakes used in the testing stage. Each circle's radius is proportional to magnitude with the largest being 5.2 ML. The blue triangles are stations used in the location of at least one test event.

above magnitude 4. The largest event is the 2008 Market Rasen earthquake with ML 5.2.

It was found that the automatic amplitudes agreed very well with those made by an experienced analyst. They were most reliable if the P-window was based on a manual P-pick. This means that amplitude measurements will only be made if there are measured phase arrival times for a given station in the database. As any clear P-arrival is generally picked, this acts as a good quality control measure, as well as ensuring that the correct window is used.

The facility to vary the window length based on the distance between earthquake and station was included in the software but in practice, the best results were found using fixed length windows. A 4 second window was used for P and a 10 second window for S. This did mean that measurements could not be made at stations very close to an earthquake, as the S-wave arrives within the first 4 seconds. For this test, readings were discarded if they were made within 30km of an earthquake. In addition, 1% of manual picks were made more than 4 seconds after the first P-arrival, generally for more distant stations where *Pg* comes in considerably later than the lower amplitude *Pn*. The automatic amplitudes in these few cases would be much too low. Perhaps the best solution for avoiding both of the above problems would be to only calculate P-amplitudes for stations where an S-pick has been made. The P-window could then have both ends delimited with confidence and would always include the maximum.

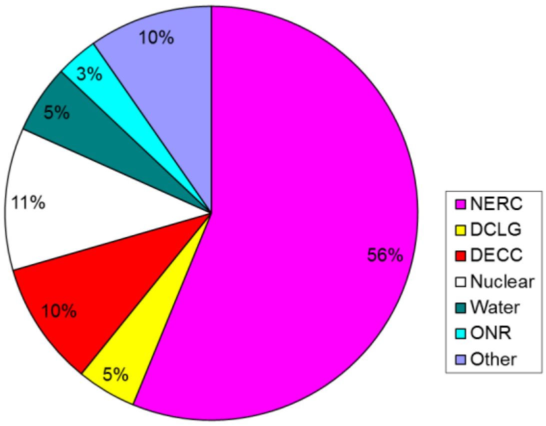
Of the different frequency bands tried, it was found that filtering between 1.5 Hz and 30 Hz was optimal. Originally, a narrowband measurement in the 0.8 Hz to 4.5 Hz band was suggested, so that the magnitudes derived could be directly compared to global m_b. However, for small earthquakes, too much energy from sea-microseisms is present in this frequency band, badly affecting the signal-to-noise ratio.

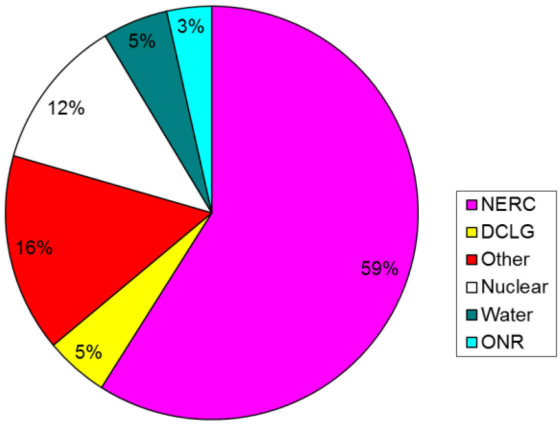


Automatic amplitudes plotted against those measured by a BGS analyst. Automatic P-amplitudes (a) are measured for a 4 second window. Automatic S-amplitudes (b) are measured for a 10 second window. The S-amplitudes are the square root of the sum of the squares of the amplitudes for the two horizontal components at a station.

Funding and Expenditure

In 2014-2015 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 £260k from the customer group drawn from industry, regulatory bodies and central and local government. In addition, approximately £200k was received from other sources, including a grant from DECC for the UKArray experiment and an AWE contract for body wave magnitude work.


2014/2015 Received


2015/2016 Expected

The projected income for 2015-2016 is approximately the same as that received in 2014-2015. The NERC contribution for 2015-2016 currently stands at £570k, but we hope to increase this through applications for additional funding through the year. The total expected customer group contribution currently stands at £247k. 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
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

Appendix 2: Publications

Albini, Paola, Musson, Roger M.W. Rovida, Andrea, Locati, Mario, Gomez Capera, Antonio A. and Viganò, Daniele, 2014 The global earthquake history. *Earthquake Spectra*, 30 (2). 607-624. 10.1193/122013EQS297

Galloway, D.D., 2016. Bulletin of British earthquakes 2014. British Geological Survey, OR/16/011.

Luckett, R. and Baptie, B., 2015. Local earthquake tomography of Scotland. *Geophysical Journal International*, 200 (3). 1538-1554. 10.1093/gji/ggu489

Sword-Daniels, V., Wilson, T.M., Sargeant, S., Rossetto, T., Twigg, J., Johnston, D.M., Loughlin, S.C., and Cole, P.D., 2014. Consequences of long-term volcanic activity for essential services in Montserrat: challenges, adaptations and resilience. In: Wadge, G.; Robertson, R.E.A.; Voight, B., (eds.) The eruption of Soufriere Hills Volcano, Montserrat from 2000 to 2010. Geological Society of London, 471-488. (Memoir, 39, 39).

Appendix 3: Publication Summaries

The Global Earthquake History

Albini, P., Musson, R.M.W., Rovida, A., Locati, M.; Gomez C., Antonio A., Viganò, D. 2014.

The study of earthquakes from historical sources, or historical seismology, was considered an early priority for the Global Earthquake Model (GEM) project, which commissioned a study of historical seismicity on a global scale. This was the Global Earthquake History (GEH) project, led jointly by the Istituto Nazionale di Geofisica e Vulcanologia (INGV; Milan, Italy) and the British Geological Survey (BGS; UK). GEH was structured around three complementary deliverables: archive, catalog, and the Web infrastructure designed to store both the archive and catalog. The Global Historical Earthquake Archive (GHEA) provides a complete account of the global situation in historical seismology for large earthquakes. From GHEA, the Global Historical Earthquake Catalogue (GHEC v1.0) was derived—a world catalog of earthquakes for the period 1000–1903, with magnitudes of Mw7 and over. Though much remains to be done, the data here presented show that the compilation of both archive and catalog contribute to an improved understanding of the Global Earthquake History.

Bulletin of British earthquakes 2014

Galloway D, D., 2016

The British Geological Survey's (BGS) Seismic Monitoring and Information Service operate a nationwide network of seismograph stations in the United Kingdom (UK). Earthquakes in the UK and coastal waters are detected within limits dependent on the distribution of seismograph stations. Location accuracy is improved in offshore areas through data exchange with neighbouring countries. This bulletin contains locations, magnitudes and phase data for all earthquakes detected and located by the BGS during 2014, listed in Tables 1 and 2. Maps showing seismic activity in 2014 (Figure 1), and the larger magnitude events since 1979 (ML> 2.5) and since 1970 (ML> 3.5) are also included. The bulletin covers all of the UK land mass and its coastal waters including the North Sea (11°W to 6°E and 47°N to 65°N). All events believed to be of true tectonic origin are included. Coalfield events are also included. Acoustic disturbances, such as sonic booms from supersonic aircraft, are included when they are felt. The airborne waves are readily identified by their slow travel time across an array or by their signature on a microphone, but they are frequently mistaken as small earthquakes by the public. They are indicated by 'SONIC' in both the locality and comments column of Table 1. Significant non-natural events, such as explosions, which received media attention or were greater than magnitude 2.5 ML or felt by local residents, are also included in Table 1. Smaller events that are known, or suspected to be of explosive origin are excluded from the bulletin where possible. These include explosions due to quarrying, mining, weapon testing or disposal, naval exercises, geophysical prospecting and civil engineering. Unfortunately, identification by record character, location and time of occurrence is not always conclusive and some man-made events may be included in the bulletin or, more rarely, a small natural event may have been excluded.

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.

Consequences of long-term volcanic activity for essential services in Montserrat: challenges, adaptations and resilience

Sword-Daniels, V., Wilson, T.M., Sargeant, S., Rossetto, T., Twigg, J., Johnston, D.M., Loughlin, S.C. and Cole, P.D.. 2014.

Long-term volcanic activity at Soufrière Hills Volcano (SHV), Montserrat (1995–ongoing) has created challenges for society and the resilience of the essential services (infrastructure) that support it. This paper explores the consequences, adaptations and resilience of essential services through interviews with their staff. We find that quick fixes for essential service reinstatement in the north of Montserrat have prevailed. Yet, the legacy of this approach inhibits functionality through inadequate facilities and the perception of sites as temporary, stalling investment. Emigration resulted in staff shortages, retraining requirements and challenges for the viability of specialist services. Low-impact hazards exacerbate shortcomings in essential services, causing power cuts, corrosion, and temporary closures of schools, clinics and the airport. Adaptations developed over time include changes to roofing materials, the addition of back-up systems, collaborative working and the development of contingency plans. Resilience of essential services has improved through decentralization, adaptations, and via strong community networks and tolerance of disruptions. Barriers to increasing resilience include the expense of some adaptations and the current reluctance to invest in essential services, hindering development. We offer some lessons for policy and practice to guide post-crisis redevelopment, through engagement with the community and by complementing community-level adaptations with investment to address long-term needs.