British
Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Earthquake Monitoring 2012/2013

BGS Seismic Monitoring and Information Service

Twenty-fourth Annual Report

BRITISH GEOLOGICAL SURVEY

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UK Earthquake Monitoring 2012/2013

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View from the vault at Eskdalemuir in winter

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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 40 broadband stations. Real-time data from all broadband stations and nearly all other short period stations are 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, 2013).

Four papers have been published in external journals. A chapter was also published in the New Manual of Seismological Observatory Practice. Three presentations were made at international conferences. Four BGS internal reports were prepared. We have continued to collaborate widely with academic partners across the UK and overseas on a number of research initiatives.

Introduction

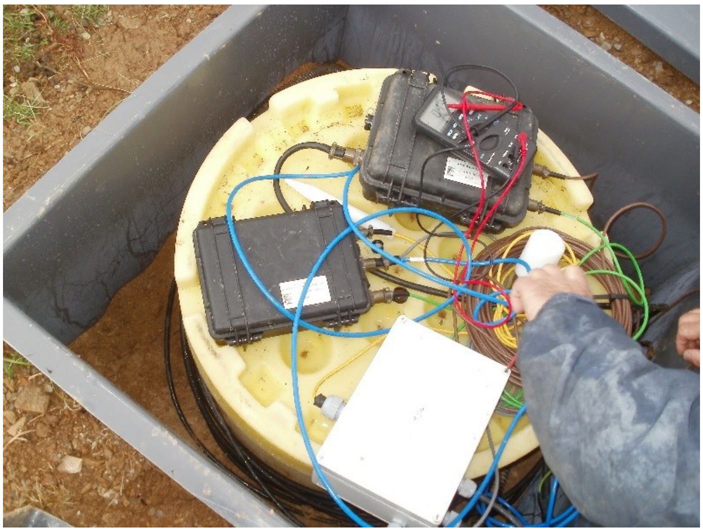
The BGS Seismic Monitoring and Information Service has developed as a result of the commitment of a group of organisations with an interest in the seismic hazard of the UK and the immediate effects of felt or damaging vibrations on people and structures. The supporters of the project, drawn from industry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

Almost every week, seismic events are reported to be felt somewhere in the UK. A small number of these prove to be sonic booms or are spurious, but a large proportion are natural or mining-induced earthquakes. Often these are felt at intensities that cause concern and, occasionally, some damage is caused. 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 2013.



Introduction

Monitoring Network

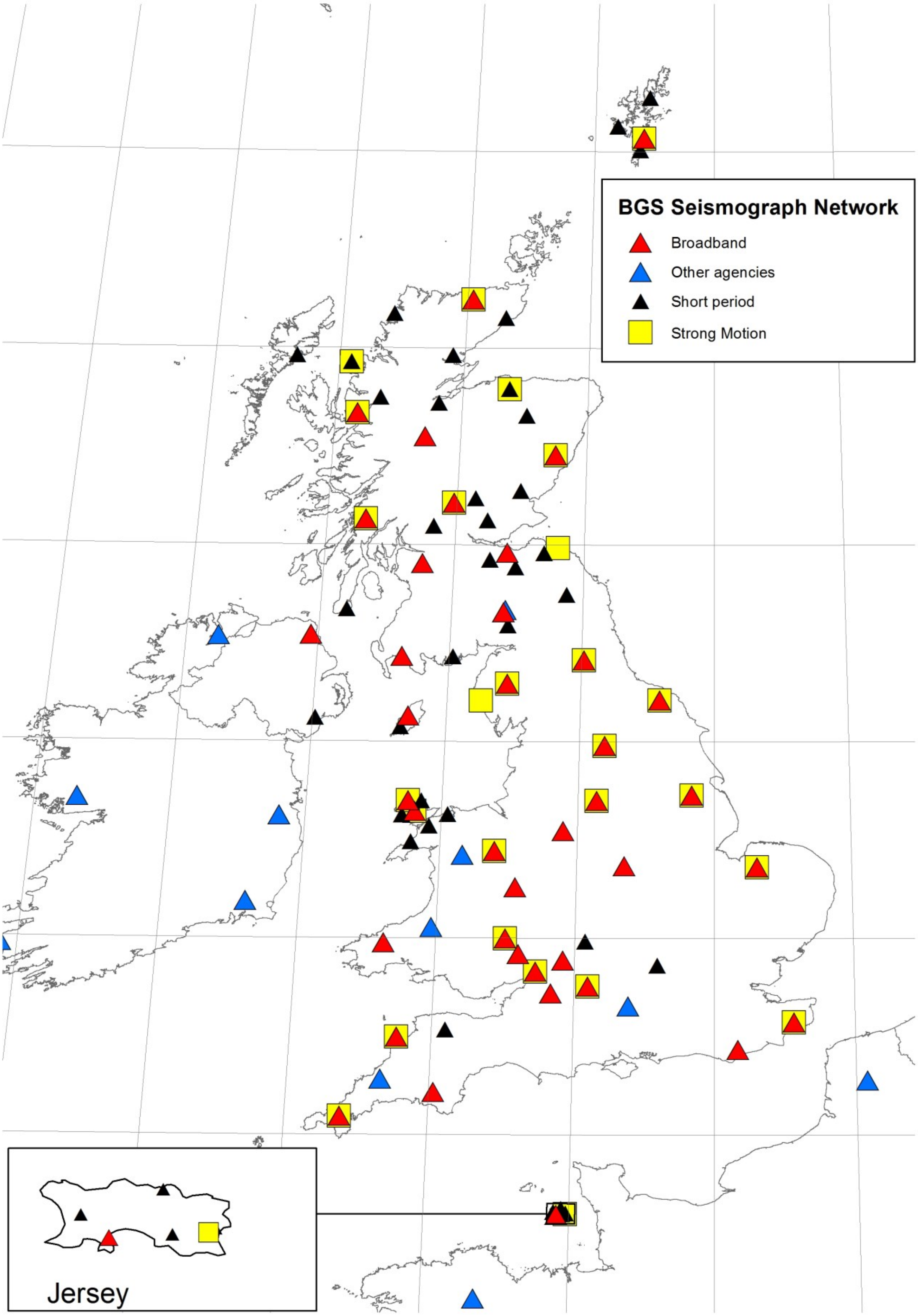
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late 1990s, the number of stations reached its peak of 146, with an average spacing of 70 km. We are now in the process 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 40 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 2013

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 at Rosebush (Pembrokeshire) and Loch Awe (Argyll). This takes the total number of broadband stations operated by BGS to 40. 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 Scottish Borders, East Anglia, Hartland and Leeds networks were decommissioned in the last year. This leaves forty operational short period stations across the UK. As more broadband stations are installed in coming years we except to decommission further short period stations. However, some short period stations will remain, such as those on Shetland and Jersey to ensure adequate detection capability. We receive continuous real-time data from all short period stations, except for stations in the Minch networks. Event data from this network is downloaded using a dial-up connection.

In addition, we have carried out site surveys for new broadband stations in Assynt, Harris, Dumfries and Galloway, 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 intend to install permanent stations in these areas in 2013.

During the year, a total of 70 field trips were made to visit stations around the UK. Of these visits, 47 were for maintenance or fault repair, 14 were to carry out site surveys for new stations, four were for installation of new stations and five were for decommissioning of old stations.

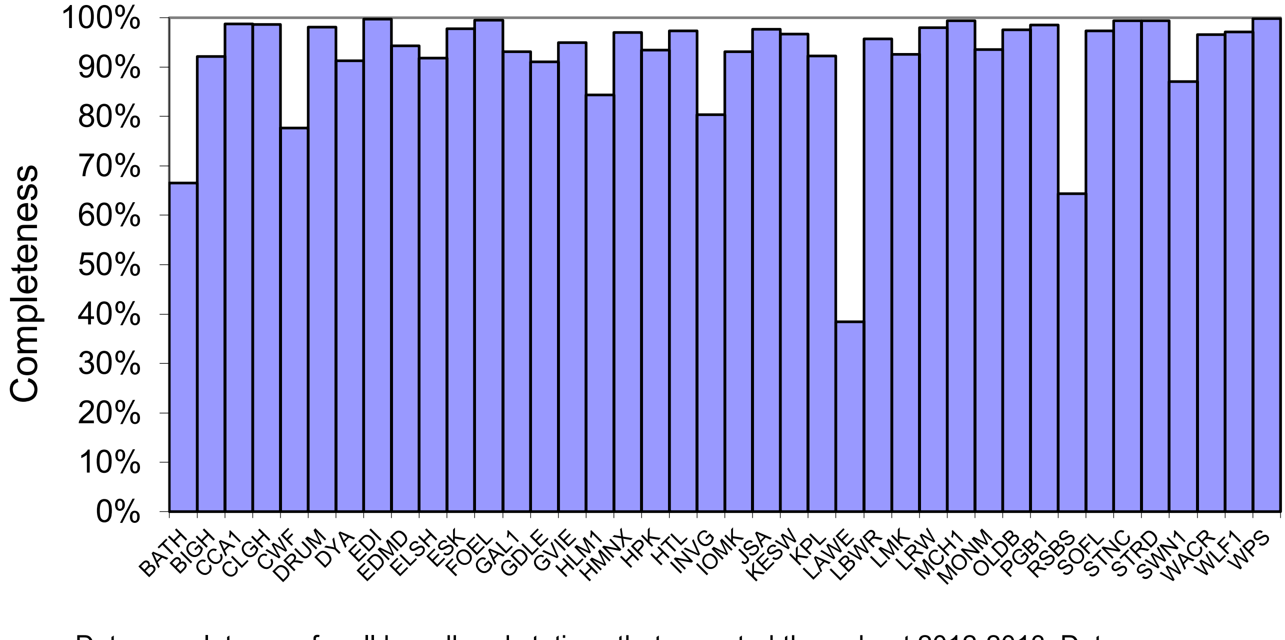
We have carried out extensive testing of the performance of the Nanometerics Trillium broadband sensor at the vault in the Eskdalemuir Observatory. This is one of the quietest locations for seismic recording the UK and allows equipment to be compared side-by-side both with each other and with a number of other long running instruments. These tests helped rectify a high frequency noise issue and the performance of the sensors is now what we would expect.

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.

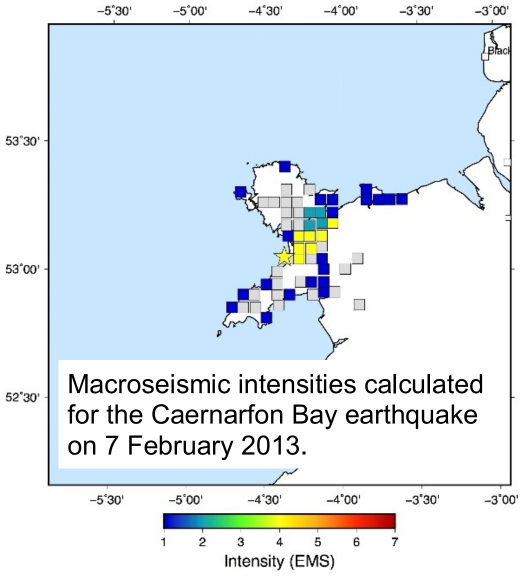
We are continuing to refine our use of the EarthWorm software, developed by the US Geological Survey and contributed to by BGS, (Johnson et al, 1995) for the automatic detection, location and notification of earthquake activity in the UK and immediate offshore area. Work is ongoing on optimisation of the picking and association modules for the current network configuration, so that our analysts receive reliable alerts for earthquakes above a given magnitude threshold.

Additionally, our EarlyBird alert system (Huang et al, 2008) continues to provide rapid notification of potentially damaging earthquakes anywhere in the world using data from over 200 stations throughout the world. Reliable locations and magnitudes are typically produced within a few minutes of the origin time.

Continuous data from all our broadband and most of our short period stations are archived at BGS. The completeness of these data can be easily checked to gain an accurate picture of network performance. In general, we find that the data from most broadband stations are over 95% complete. 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.



Data completeness for all broadband stations that operated throughout 2012-2013. Data are more than 90% complete for more than 80% of stations and more than 95% complete for over 50% of stations. Note that stations LAWE and RSBS were installed during the year.



Macroseismic intensities calculated for the Caernarfon Bay earthquake on 7 February 2013.

Achievements

Information Dissemination

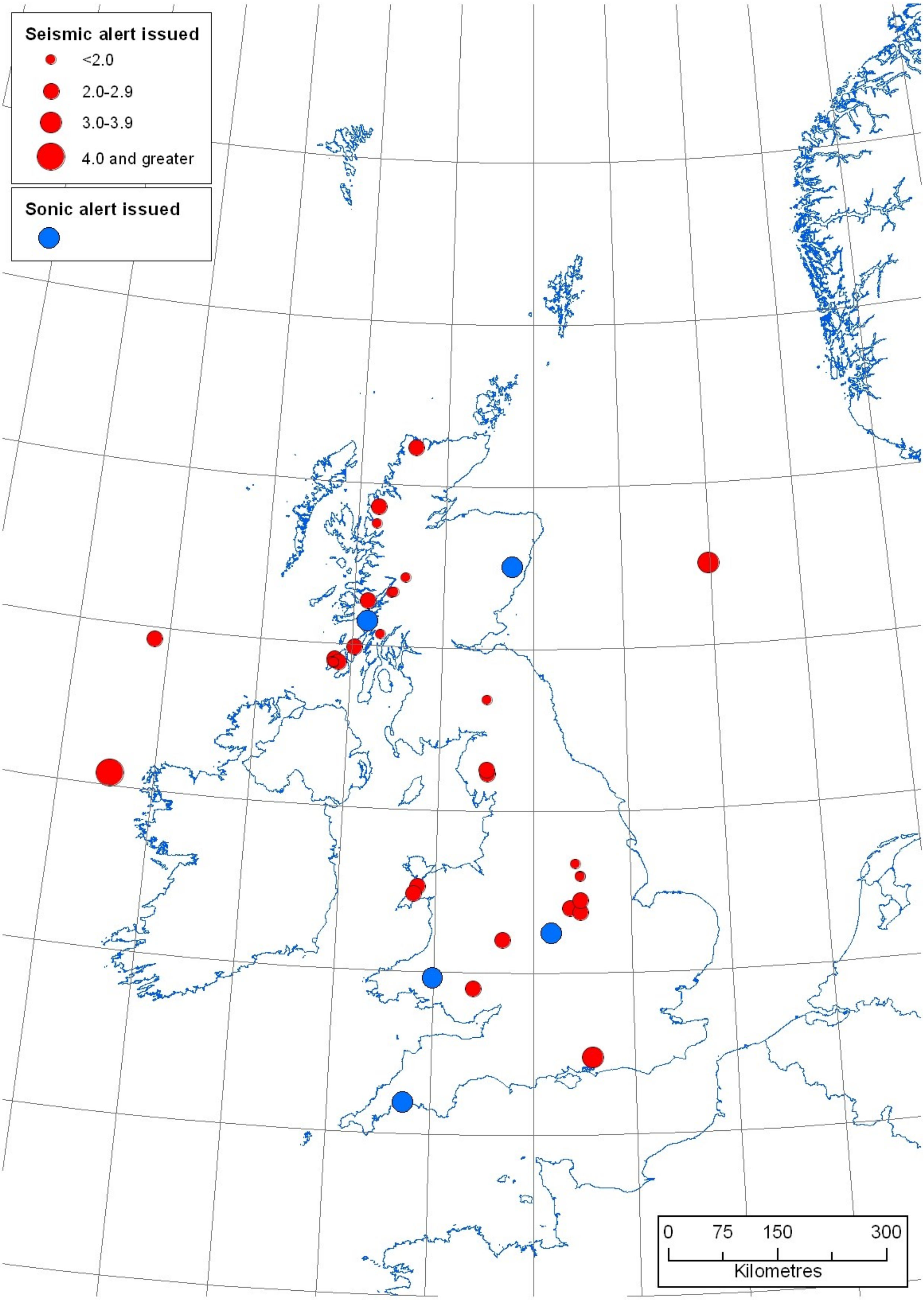
It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received notification by e-mail whenever an event was felt or heard by more than two individuals.

Notifications were issued for 40 UK events within the reporting period, five of which were of a sonic origin. 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, a single enquiry was received from Nuclear Power Stations after alarms triggered at Wylfa on 16 November 2012. 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 providing near real-time lists of 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 335 replies following the Loughborough earthquake on 18 January 2013 (2.9 ML) and 231 replies after a magnitude 2.3 ML earthquake on 7 February 2013 in Caernarfon Bay.

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.

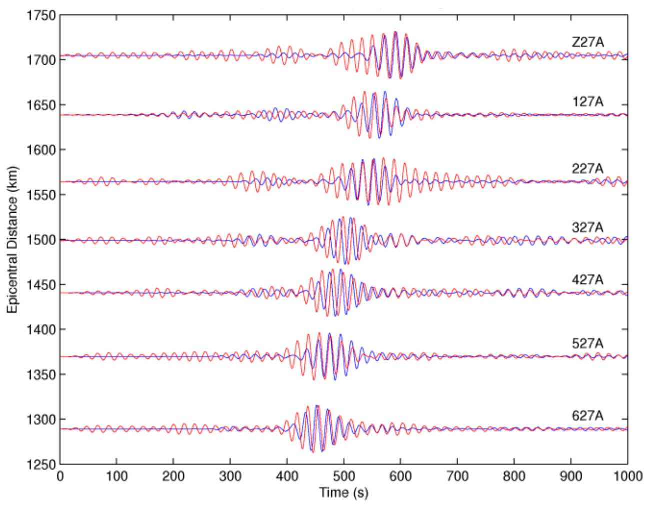


Events in the reporting period (1 April 2012 to 31 March 2013) for which alerts have been issued. Circles are scaled by magnitude. The blue circles show the places where the suspected sonic events were felt. Eight of the alerts are outside the map extent.

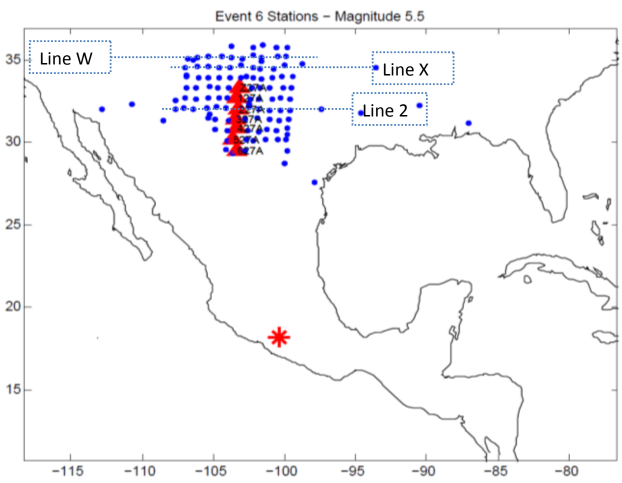
Collaboration and Data Exchange

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 in the second year of a PhD project, 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. This can happen hours, days, or even months after the earthquake has occurred, providing the subsurface through which the seismic waves propagate does not change i.e. providing the EGFs calculated between seismometer pairs do not change in the time between their calculation and the occurrence of the earthquakes. This work is being carried out using the USArray seismic network.



Interferometric results (red) compared with the real recordings of the earthquake (blue) at the same locations.



Interferometry: the aim is to reconstruct the earthquake (red star) at the stations marked by red triangles using data recorded on the seismometer array (blue dots).

A BGS CASE student at the University of Cambridge started her PhD in October 2012 following an ongoing line of research into the causes of regional uplift in the British Isles. During this project an array of seismometers will be deployed across Scotland to provide data for a detailed investigation of the Earth's Crust and Upper Mantle under the northern part of the British Isles. Thinner crust beneath northwest Scotland may suggest that present-day topography is maintained by regional dynamic support, originating beneath the lithosphere.

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. A new post-doctoral researcher was recruited to work on this project in October 2012.

Roger Musson is working 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 (http://www.nerc.ac.uk/research/funded/programmes/pure/).

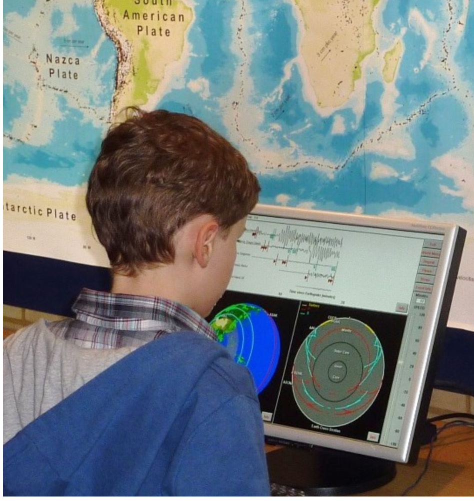
BGS are working with GFZ Potsdam, University of Weimar and Cambridge Architectural Research on the development of the European Macroseismic Scale for world-wide use. They are also working with INGV Milan on the Global Historical Earthquake Archive, a module within the Global Earthquake Model project (GEM) – the work was completed in December 2012.

The European Mediterranean Seismological Centre (EMSC), BGS and others have continued to collaborate on development of online macroseismic surveys, now within the framework of a European Seismological Commission (ESC) working group on Internet Seismology.

Susanne Sargeant visited Dhaka, Bangladesh in November 2012 to 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.

Richard Luckett visited Ethiopia in August 2012 to help the Institute of Geophysics, Space Science and Astronomy (IGSSA) to set up near real-time data acquisition and processing for a number of seismic stations around Ethiopia. These stations are vital for providing objective data on both seismic and volcanic activity.

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 483 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 following significant earthquakes. Earthquake lists, maps and specific pages are generated and updated automatically whenever a new event is entered in our database or when the parameters for an existing event are modified. This year we have added a database search page that allows users to search our database for basic earthquake parameters within a given geographic or magnitude range. We have also continued to provide displays of real-time data from most of our seismic stations that allow users to check activity or look for specific events. In addition, we continue to add event-specific content for significant earthquakes in the UK and around the world. These document the parameters of these events and provide information on the tectonic setting and background seismic activity in the region.

The seismology web site continues to be widely accessed, with over 819,000 visitors logged in the year (over 8.9 million hits). Small peaks (less than twice the daily average) were observed following the West Ireland earthquake of 6 June 2012 and the Loughborough earthquake (18 January 2013).

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.

Paul Denton from BGS continues to lead the Networking School Seismology Programs work package (NA8) of the EU project Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation (NERA). NERA is an EU infrastructure project that integrates key research infrastructures in Europe for monitoring earthquakes and assessing their hazard and risk. NERA NA8 aims to foster the integration of school seismology projects across Europe, and to set up a data exchange system and to share best practice in teaching activities and resources (http://www.nera-eu.org).

In June 2012, a school seismometer was used in the OCR A2 (Advanced Physics) exam paper under the Fields and Particles section.

In September 2012, BGS hosted the annual Earth Science Teachers Association conference, a chance for Geology teachers across the UK to meet up and exchange ideas (http://www.esta-uk.net/).

A book written by Roger Musson, “The Million Death Quake”, was published in November 2012, (Musson, 2012). The book examines the dangers of megaquakes, and explains where they will next strike, why they are becoming more lethal, and what science and engineering are doing to save lives.

Brian Baptie featured in BBC Radio 4's The Listeners programme, broadcast on 28 February 2013. The programme discussed making earthquake waves audible to the human ear.

In March 2013, Davie Galloway and Paul Denton from BGS participated in the The Association for Science Education (ASE) conference in Crieff, Scotland, promoting school seismology and BGS outreach.

The 2012 BGS Open Day attracted 943 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 2012-2013, at least 1,826 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 2012, published and distributed in Galloway (2013).

There were 125 local earthquakes located by the monitoring network during 2012-2013, with 35 having magnitudes of 2.0 ML or greater, seven having magnitudes of 3.0 ML or greater, and one with a magnitude of 4.0 ML. Sixteen events with a magnitude of 2.0 ML or greater were reported felt, together with a further 31 smaller ones, bringing the total to 47 felt earthquakes in 2012-2013.

A magnitude 2.8 ML earthquake occurred on 1 June 2012 at 12:16 UTC near Ludlow, Shropshire. The earthquake was felt in Craven Arms, 14 km to the west and Clee St. Margaret, 5 km to the north. The maximum intensity was 3 EMS (European Macroseismic Scale).

A magnitude 2.7 ML earthquake occurred on 31 October 2012 at 15:59 UTC on the island of Jura, Argyll and Bute. A single felt report was received from the neighbouring island of Islay.

A magnitude of 2.9 ML earthquake occurred on 14 December 2012 at 23:03 UTC, approximately 13 km north-northwest of Chichester, Sussex. The earthquake was felt in Chichester, Bognor Regis and Midhurst (West Sussex), Haslemere, Hindhead (Surrey), Liphook (Hampshire) and Brighton (East Sussex). This was the joint largest earthquake that occurred in the reporting period. The maximum intensity was 3 EMS.

The largest offshore earthquake occurred on 6 June 2012 at 07:58 UTC, approximately 60km west of Belmullet, County Mayo. It had a magnitude of 4.0 ML and was widely felt in the Irish Republic across the counties of Mayo, Sligo and Galway. This was the largest earthquake to be felt in Ireland since the Lleyn Peninsula earthquakes in 1984 and was an unusual event given the relative lack of significant seismic activity in this region. Six other earthquakes with magnitudes greater than or equal to 3.0 ML were also detected in offshore areas. All of these were in the central or northern North Sea, several hundred kilometres from the British coast.

The UK monitoring network also detects large earthquakes from around the world, depending on the event size and epicentral distance. Recordings of such earthquakes can be used to provide valuable information on the properties of the crust and upper mantle under the UK, which, in turn, helps to improve location capabilities for local earthquakes. During the period April 2012 to March 2013, a total of 432 teleseismic earthquakes were detected and analysed.

Epicentres of all earthquakes in and around the UK detected in the reporting period (1 April 2012 – 31 March 2013).

Seismic Activity

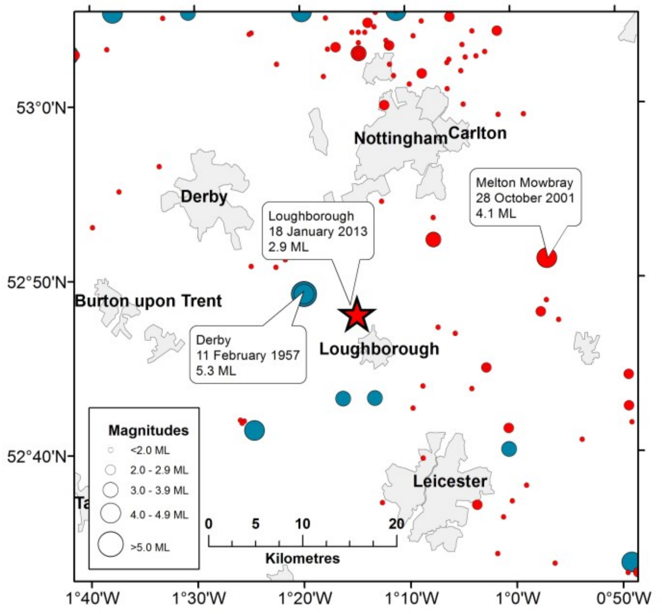
The Loughborough Earthquake

A magnitude 2.9 ML earthquake occurred near Loughborough, Leicestershire on18 January 2013 and was the joint largest onshore earthquake in the reporting period. The earthquake was felt widely at distances of up to 100 km from the epicentre and with a maximum intensity of 4 EMS.

A magnitude 2.9 ML earthquake occurred on 18 January 2013 at 05:20 UTC, near Loughborough, Leicestershire. The earthquake was well-recorded by the BGS seismometer network at distances of up to 300 km. The hypocentre was calculated from 14 P-wave arrival times and five S-wave arrivals times. The hypocentral depth was 13.5 km. The magnitude of 2.9 ML was determined from amplitudes measured at five stations at distances of 8 to 127 km.

This part of England has experienced some notable earthquakes in the past. For example, a magnitude 5.3 ML earthquake south 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 of the 1957 earthquake was approximately 6 km east of the Loughborough earthquake, near Mead, Castle Donnington. More recently, a magnitude 4.1 ML earthquake near Melton Mowbray on 28 October 2001 was approximately 28 km to the east.

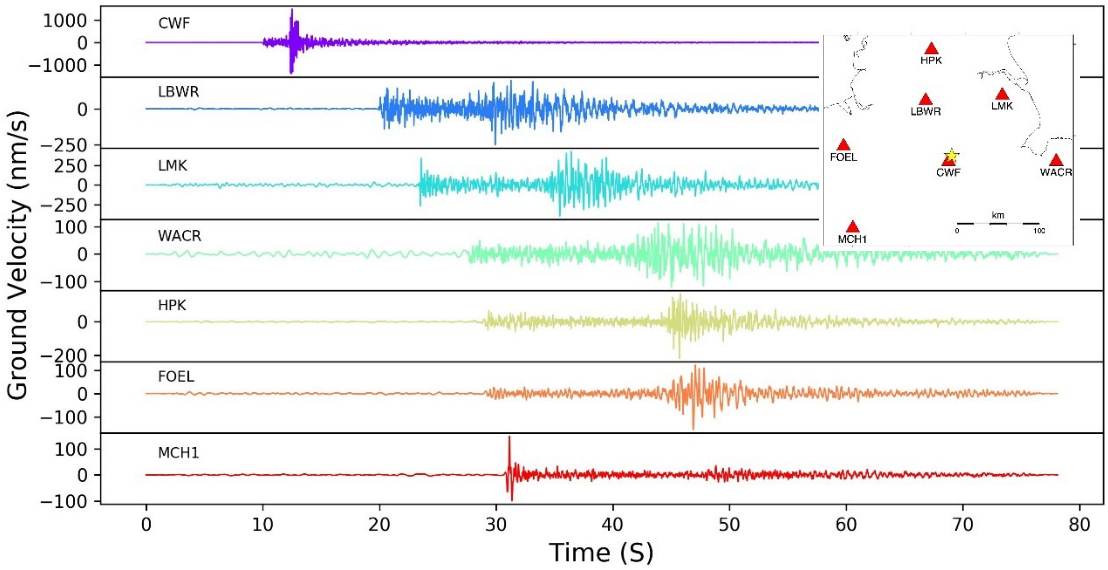
An earthquake of this magnitude and depth (13.5 km) would typically be felt up to a distance of up to 60 km from the epicentre. Analysis of the results from the online questionnaires broadly agrees with this. A total of 335 reports were received from 100 different places. The majority of these



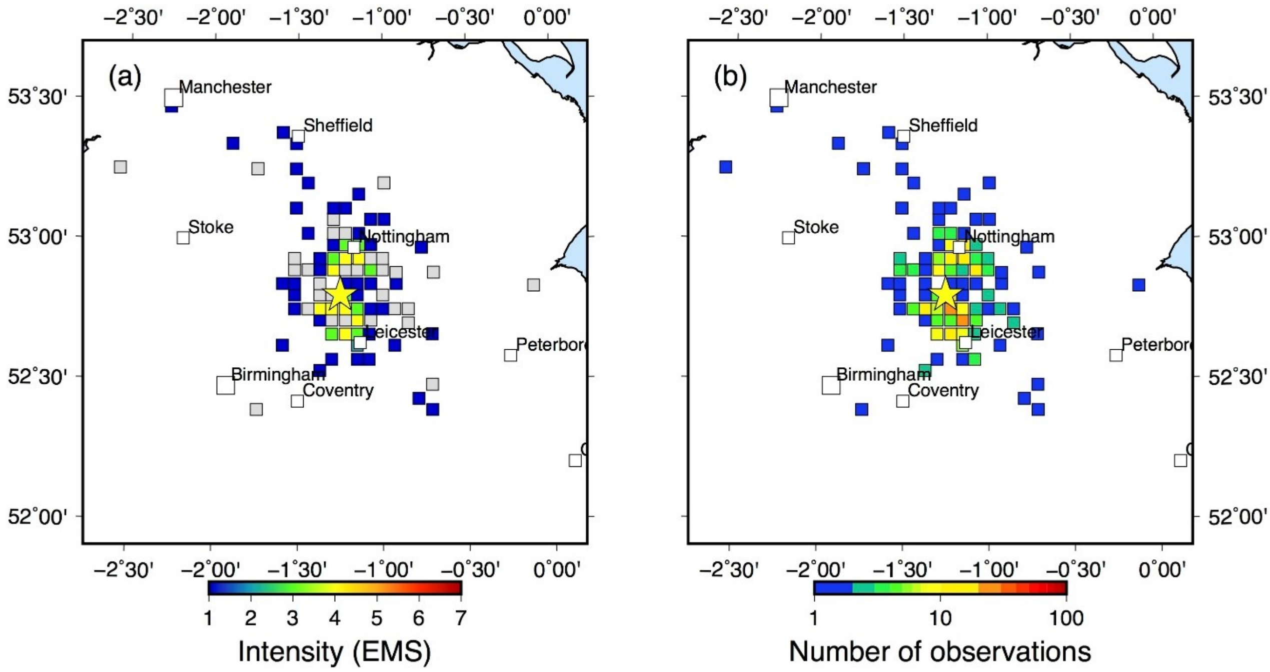
Instrumental (red) and historical (blue) seismicity around Loughborough.

reports came from within a 25 km radius of the epicentre, namely from the towns of Loughborough, Derby, Leicester and Nottingham. Around 20 credible reports were received from beyond this area with the furthest afield being from near Buxton (60 km to the NNW), near Warwick (55 km to the SE) and Corby (50 km to the SSE). The felt area was elongated in an NNW-SSE direction, the long axis being about 120 km and the short axis around 65 km.

The maximum intensity of the earthquake was weak-moderate (4 EMS) with many people being woken from sleep. Reports described “the bed rattled and the books fell off the shelf", "first a rumble, then felt the wave move from front to back of house", "like a slow distant grumble and then the force seemed to come up stronger, my bed was shaking, the noise was louder and then faded away", "sounded like an impact blast from an explosion because it made the window vibrate", "sounded like a train or lorry crashing then a shake of house" and "sounded like a large lorry passing along a road some distance away".



Ground motions recorded by BGS seismic stations from the magnitude 2.9 ML earthquake that occurred on18 January 2013 at 05:20 UTC, near Loughborough, Leicestershire.



(a) Macroseismic intensities calculated for the magnitude 2.9 ML Loughborough earthquake on 18 January 2013. 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.

Seismic Activity

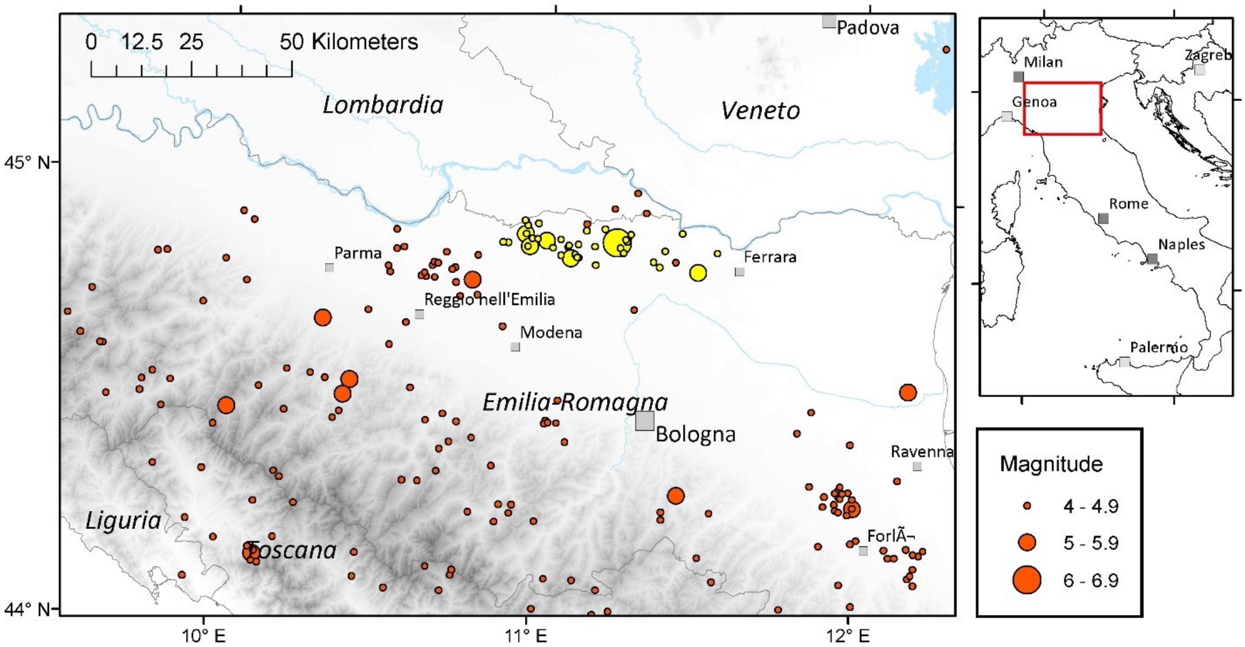
Overview of global earthquake activity

Worldwide, there were seventeen earthquakes with magnitudes of 7.0 or greater and 136 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.

A magnitude 6.0 earthquake struck the Emilia region of northern Italy on 20 May 2012, approximately 30km west of the town of Ferrara. The mainshock triggered a seismic sequence of over 1500 aftershocks that lasted for over a month. The sequence contained six more events with ML ≥ 5, including a magnitude 5.9 earthquake on 29 May, and about 80 earthquakes with ML ≥ 3.5 (Scognamiglio et al.2012).

The earthquakes resulted in 17 deaths, significant damage to historic structures, churches and industrial buildings, and emergency shelter was needed for over 13,000 people. Seismic hazard in this part of northern Italy had been considered relatively low.

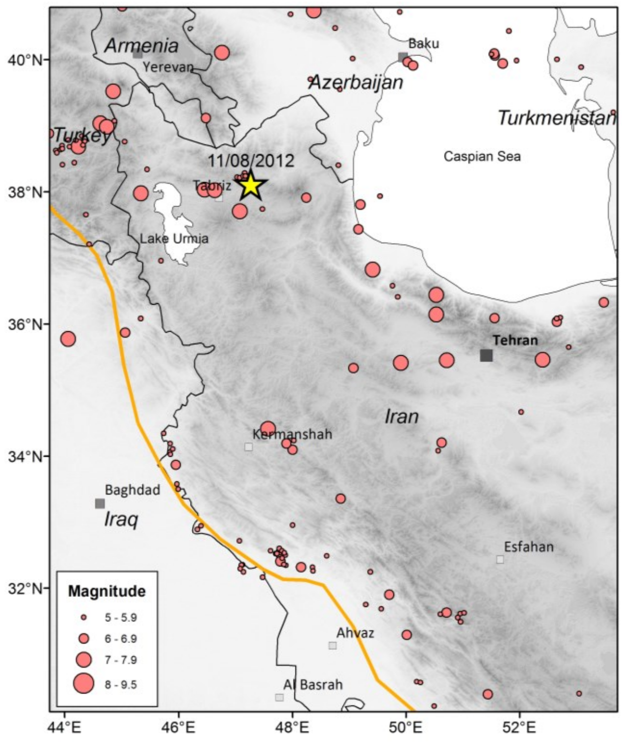
The earthquake affected a large area that included the provinces of Modena, Ferrara, Rovigo, and Mantova. A peak ground acceleration (PGA) of 0.27g was recorded at an epicentral distance of 16 km (Chioccarelli et al. 2012).



Earthquake activity in the Emilia Romagna region of northern Italy. Yellow circles show the Emilia seismic sequence. Red circles show previous earthquakes. Circles are scaled by magnitude.

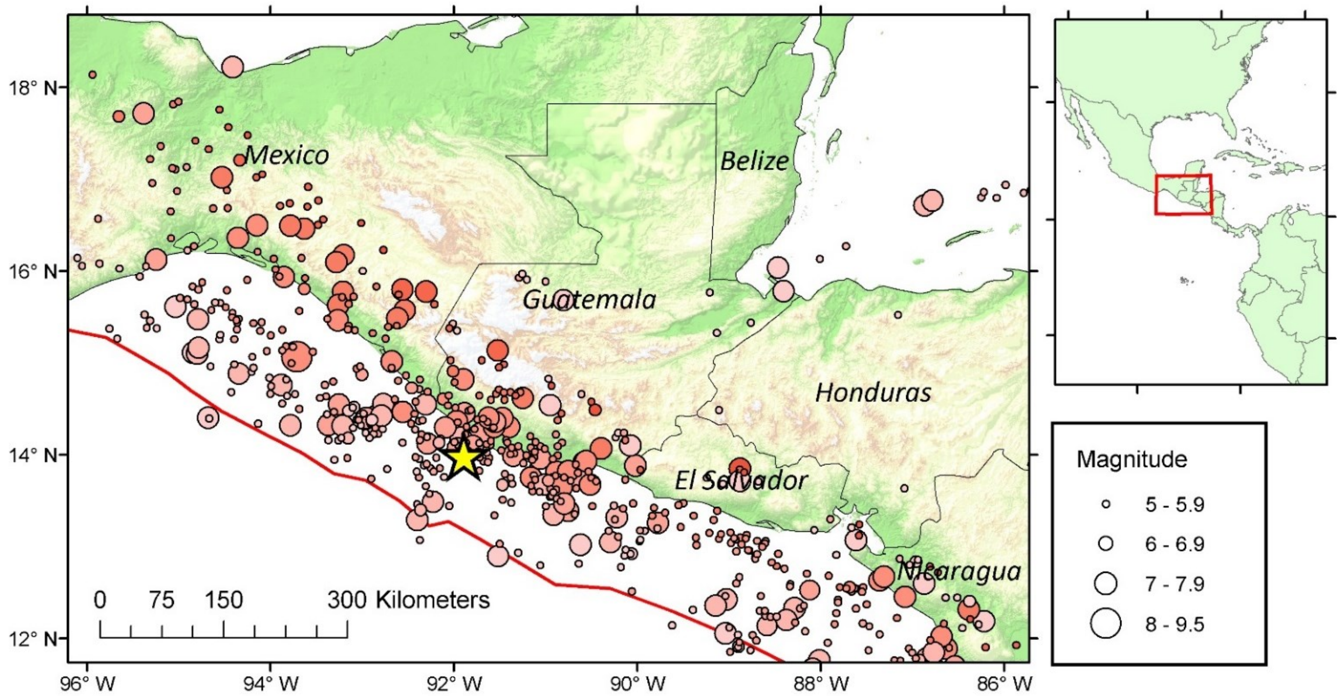
A magnitude 5.6 earthquake struck northeast Yunnan province on 7 September 2012 close to the border with both Sichuan and Guizhou provinces. Chinese state media reported that at least 81 people died in the earthquake and more than 800 were injured. The earthquake was followed by a magnitude 5.3 earthquake a few hours later that contributed to the damage.

On 11 August 2012, two earthquakes with magnitudes of 6.4 and 6.2 struck northwest Iran, 54 km northeast of the city of Tabrīz. The earthquakes were eleven minutes apart. Over 300 people were killed and over 3,000 were injured. A number of villages in the epicentral area were destroyed and many were heavily damaged.



Earthquake activity in northwest Iran (circles). Circles are scaled by magnitude. The yellow star shows the epicentre of the earthquakes on 11 August 2012.

On 7 November 2012 a magnitude 7.4 earthquake off the west coast of Guatemala resulted in over one hundred deaths, thousands of injured and many thousands lost their homes. The epicentre was close to the city of Champerico, but the earthquake also caused damage in the cities of San Marcos, Quetzaltenango and the capital Guatemala City. The earthquake occurred as a result of thrust faulting between the subducting Cocos plate and the overlying Caribbean and North America plates. At this point, the Cocos plate is moving north-northeast with respect to the Caribbean and North America plates at a rate of approximately 70-80 mm/year.



Earthquake activity in Central America (circles). Circles are scaled by magnitude and coloured by depth. The yellow star shows the epicentre of the magnitude 7.4 earthquake on 7 November 2012.

Scientific Objectives

Earthquakes Without Frontiers

Earthquakes Without Frontiers is a partnership for increasing resilience to seismic hazard in the Alpine-Himalayan belt that brings together both physical and social scientists from across the UK. This consortium is funded by the UK's Natural Environment Research Council (NERC) and Economic and Social Research Council (ESRC) with a total budget of £4 million over five years.

The Earthquakes Without Frontiers (EWF) project brings seismologists from the British Geological Survey together with natural and social scientists from Cambridge, Durham, Hull, Leeds, Northumbria and Oxford universities, the Overseas Development Institute and the National Centre for Earth Observation. The partnership extends across the Alpine-Himalayan belt: a vast region that accommodates the collision between the Eurasia plate and the Africa and India plates. We have collaborators in Italy, Greece, Turkey, Iran, Kazakhstan, Kyrgyzstan, India and Nepal.

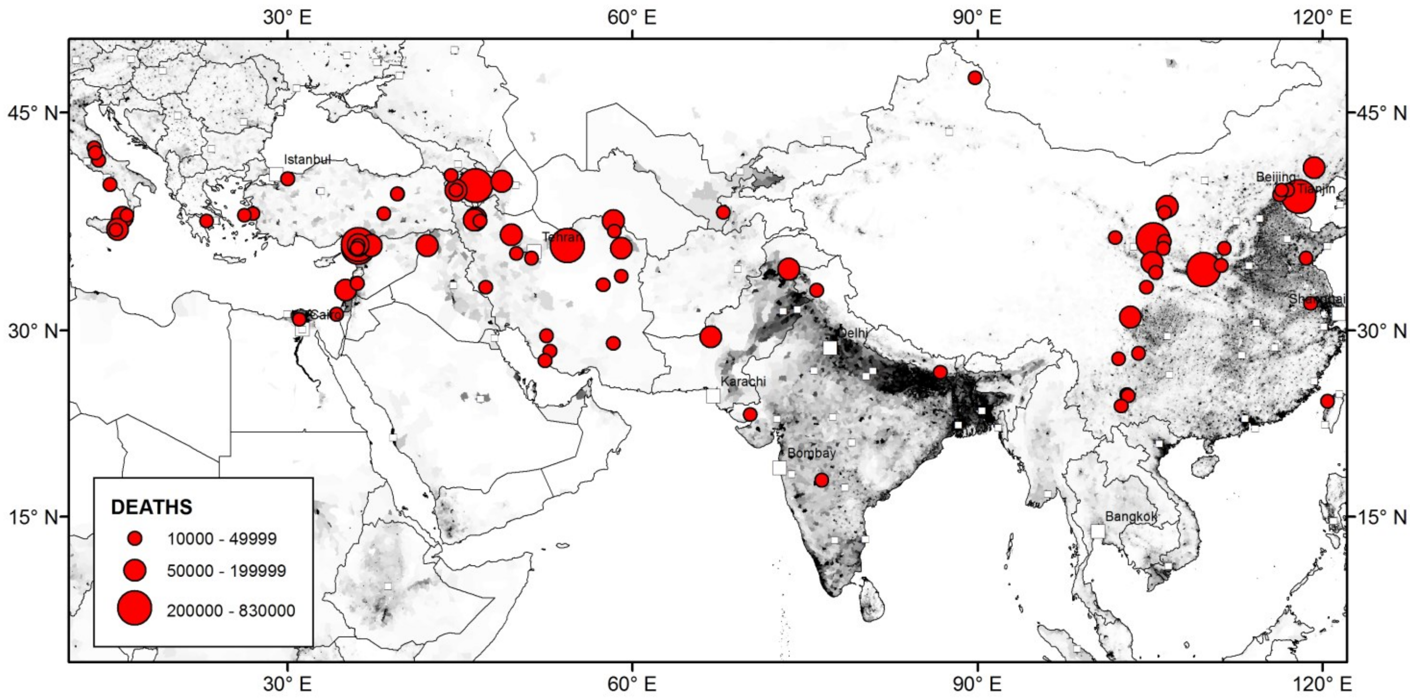
The collision between Eurasia, Africa and India is taken up on numerous faults distributed over a wide region unlike at a subduction zone or at a strike-slip plate margin where the plate boundary is relatively narrow and well-defined. Of the approximately 2-2.5 million people who have died in earthquakes since 1900, approximately two thirds of those deaths have occurred as a result of earthquakes in regions like the Alpine-Himalayan collision zone (England and Jackson, 2011). While our understanding of earthquakes and earthquake hazard in the continental interiors has advanced considerably since 1900, there are still important gaps in our understanding, which must be filled. Furthermore, as populations increase and cities grow, a growing number of people are exposed to earthquake hazard and are living in very vulnerable buildings. Understanding what makes communities resilient to earthquakes, and facilitating the development of greater resilience is also vital.

To meet the challenges that relate to increasing resilience to seismic hazard, EWF brings together a group of earth scientists (seismologists, geologists, remote sensing specialists, etc.) with a long track record in integrated earthquake science, social scientists who have extensive experience in exploring the vulnerability and resilience of communities in disaster-prone regions, and experienced practitioners in the communication of scientific knowledge to decision makers.

The project has three overarching objectives:

1. To provide transformational increases in knowledge of the distributions of primary and secondary earthquake hazards (mainly landslides) in the continental interiors.
2. To identify pathways to increased resilience in the populations exposed to these hazards.
3. To secure these gains in the long term by establishing a well-networked, transdisciplinary partnership for increasing resilience to earthquakes.

The research is focused on three regions: north-eastern China, Iran and Central Asia, and the Himalayan mountain front. In each of these regions, we will be working closely with local scientists, policy makers and both governmental and non-governmental organisations. BGS seismologists are contributing to research relating to ground motion modelling and seismic hazard assessment, and to the wider transdisciplinary process. This draws on our experience of working with a range of stakeholders and decision makers on issues that are related to seismic hazard, risk and resilience. In this early part of the project, BGS activities are particularly focused on Kazakhstan where we are building links with national seismological and geophysical institutes. Our aim is to develop joint research projects that are linked to wider disaster risk reduction and resilience-building activities in the country.



Red circles are earthquakes since 10000 AD that are known to have caused more than 10,000 deaths, graded in size from 10,000 to 800,000 deaths in each event. Data is from the NOAA Significant Earthquake Database (http://www.ngdc.noaa.gov/hazard/earthqk.shtml). Shading shows population density across earthquake-prone areas in continental Asia.

Scientific Objectives

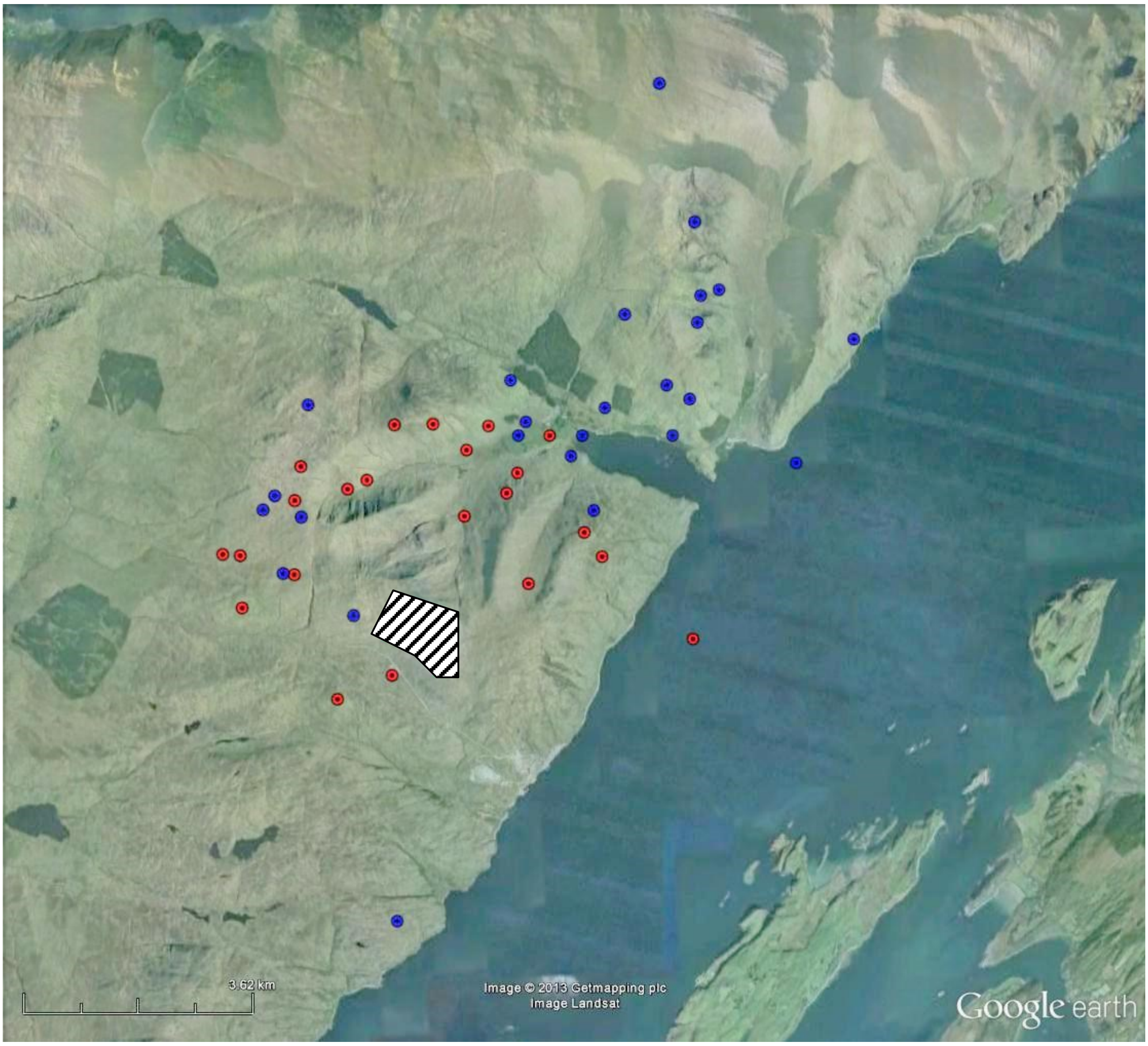
Tomography Results for Scotland

Local earthquake tomography has been completed for Scotland. A careful selection was made from the earthquakes located by the BGS over the last four decades to provide a dataset maximising arrival time accuracy and ray-path coverage. These travel times have been used in an inversion to retrieve a 3-D velocity model. When used to relocate quarry blasts this model gives a marked improvement over the currently used 1-D model.

Local earthquake tomography (Kissling et al, 1994, Thurber, 1993) is a passive method to image the seismic velocity of the crust. It depends on earthquake sources within the model volume recorded at local stations. Although earthquake activity in Scotland is low, there has been thirty years of continuous seismic monitoring with a network of relatively high station density, as well as a number of temporary deployments. This means that there is now a sufficient number of earthquakes recorded within the proposed source volume for local earthquake tomography to be used to determine a 3-D model of seismic velocity under Scotland. This tomographic study has been completed and is currently being published, along with the resulting 3-D model.

The resolution of the final 3-D model is variable, with those areas with high earthquake activity (such as the West Coast) having much better ray path coverage. In these areas of high resolution, the model shows good agreement with previously published interpretations of seismic refraction and reflection experiments. 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.

As a test of the usefulness of the new model for earthquake location, 54 well recorded, confirmed quarry blasts were relocated. These quarry blasts were not used in the inversion and so the test is independent of the models calculation. The accuracy of the old and new locations was assessed by how far they were from the actual location of the quarry. On average, the blasts relocated using the new model are within 4km of the relevant quarry – compared to an average of just over 5km using the existing 1-D model. Location errors were, however, not uniformly distributed between the quarries. The quarries at the edge of the new model, where it is acknowledged to be less accurate, had much larger errors than those within the area of the models highest resolution and in some cases (one quarry on Orkney, for example) the new model made the relocation worse than before. It was decided to relocate only those quarry blasts from the Glensanda quarry in the north-west highlands. These account for about half of the quarry events being used (26 blasts) and the quarry is located in the centre of the new model where coverage is best. As the figure shows, these locations are markedly more accurate when calculated using the new model than with the 1-D model – the average distance from the quarry has fallen from 5359m to 3278m.



Epicentres found for quarry blasts originating at Glensanda quarry. The quarry is indicated by the hatched area, blue circles show locations in the database for these events and red circles the relocations using the 3-D model.

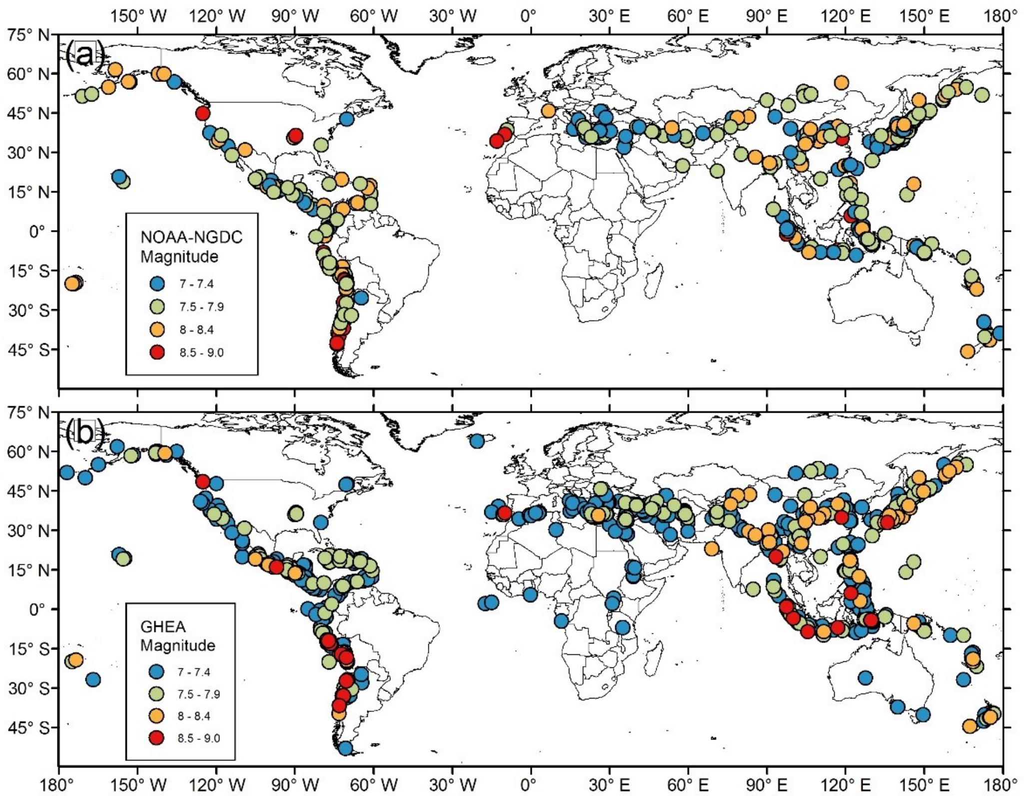
Scientific Objectives

The Global Historical Earthquake Archive

The Global Historical Earthquake Archive (GHEA) project (Albini et al, 2013), led jointly by INGV (Milan, Italy) and BGS, was one of the first "global modules" commissioned by the Global Earthquake Model (GEM) project, and was successfully completed in December 2012. It was structured around three complementary deliverables: archive, catalogue and the web infrastructure designed to store both archive and catalogue data, and the final product provides a complete account of the global situation in historical seismology.

The catalogue, entitled the Global Historical Earthquake Catalogue (GHEC v1.0), covers the period from 1000-1903 with magnitude 7 Mw and over, although in some low-seismicity parts of the world the threshold was lowered to 6.5 Mw or even 6 Mw. It is intended to be the best global historical catalogue of large earthquakes presently available, with the best parameters selected, duplications and fakes removed, and in some cases, new earthquakes discovered.

For the period 1000-1903, there are 422 events of 7 Mw or greater in the NOAA Significant Earthquake Database; whereas there are 715 in the GHEC. The difference

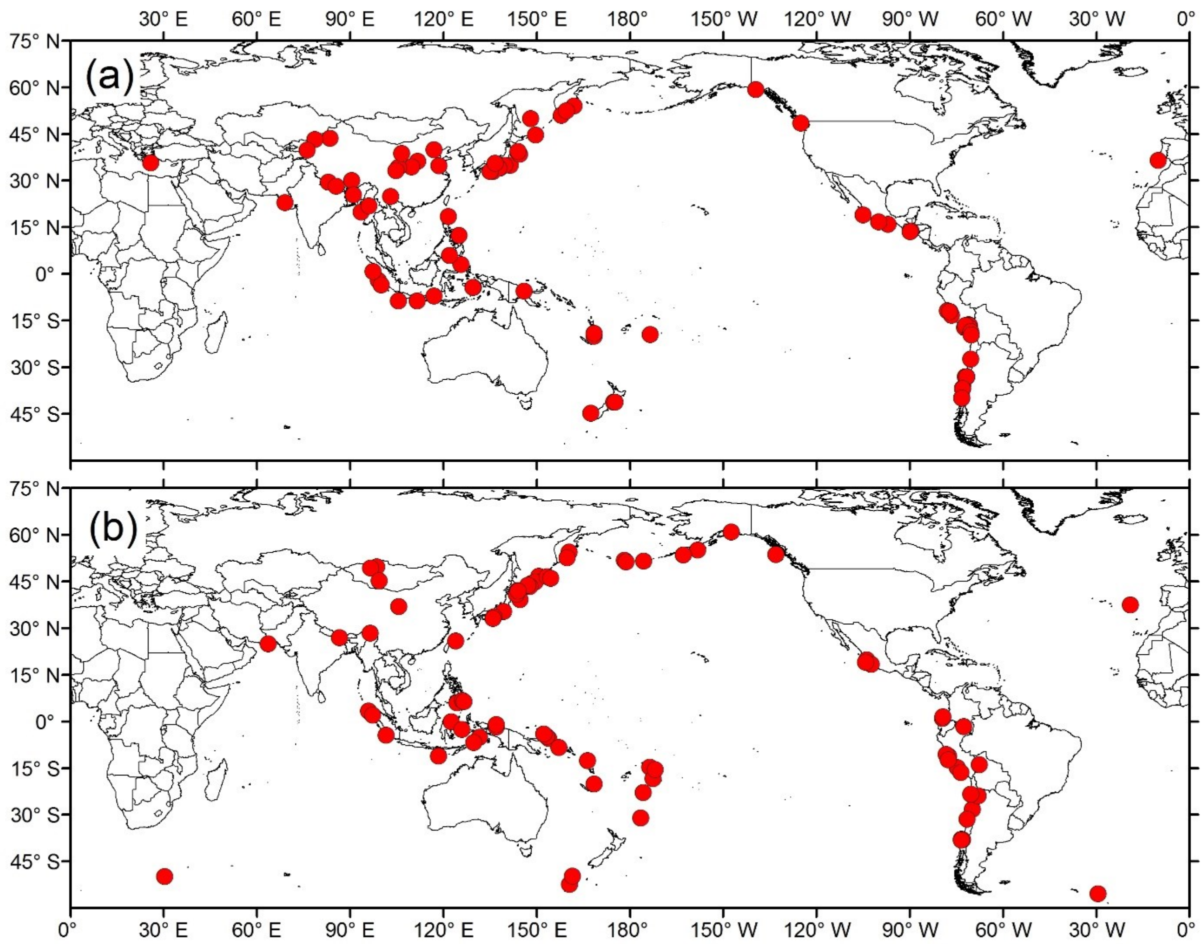


Earthquakes with magnitudes above 7 in the time period 1000 to 1903 in (a) the NOAA significant earthquakes catalogue and (b) the GHEC.

is particularly stark in Indonesia, which was previously very poorly represented in historical catalogues.

It would be a natural impulse to expect to use this new catalogue to address questions of global moment release rates and the nature of the tail in the global upper magnitude distribution. Unfortunately, one of the lessons of this project is that such expectations are unrealistic. Even for earthquakes above 8 Mw, there is no global completeness. For the period 1800-1899 there were 38 earthquakes above 8 Mw; in the period 1900-1999 there were 72. This sort of disparity is unlikely to be a real change in rate, and the geographical areas where the shortfall is most acute are remote areas like the Aleutians. The problem is partly that deep earthquakes are very hard to reconstruct from historical data, and partly that in remote areas, a great earthquake may be known about, but there is often insufficient information for one to be able to estimate the magnitude reliably.

So although the new GEM historical earthquake catalogue is a global resource, it should be thought of primarily as a resource for regional studies. As a web-enabled resource (http://emidius.eu/GEH/), it is likely to be much sought after for information about the largest earthquakes that have occurred in the historical period, anywhere in the world.



(a) Earthquakes with magnitudes above 8 in the time period 1800-1899 in GHEC and (b) earthquakes with magnitudes above 8 in the time period 1900-1999 in the ISC-GEM catalogue.

Scientific Objectives

Ambient Noise Tomography

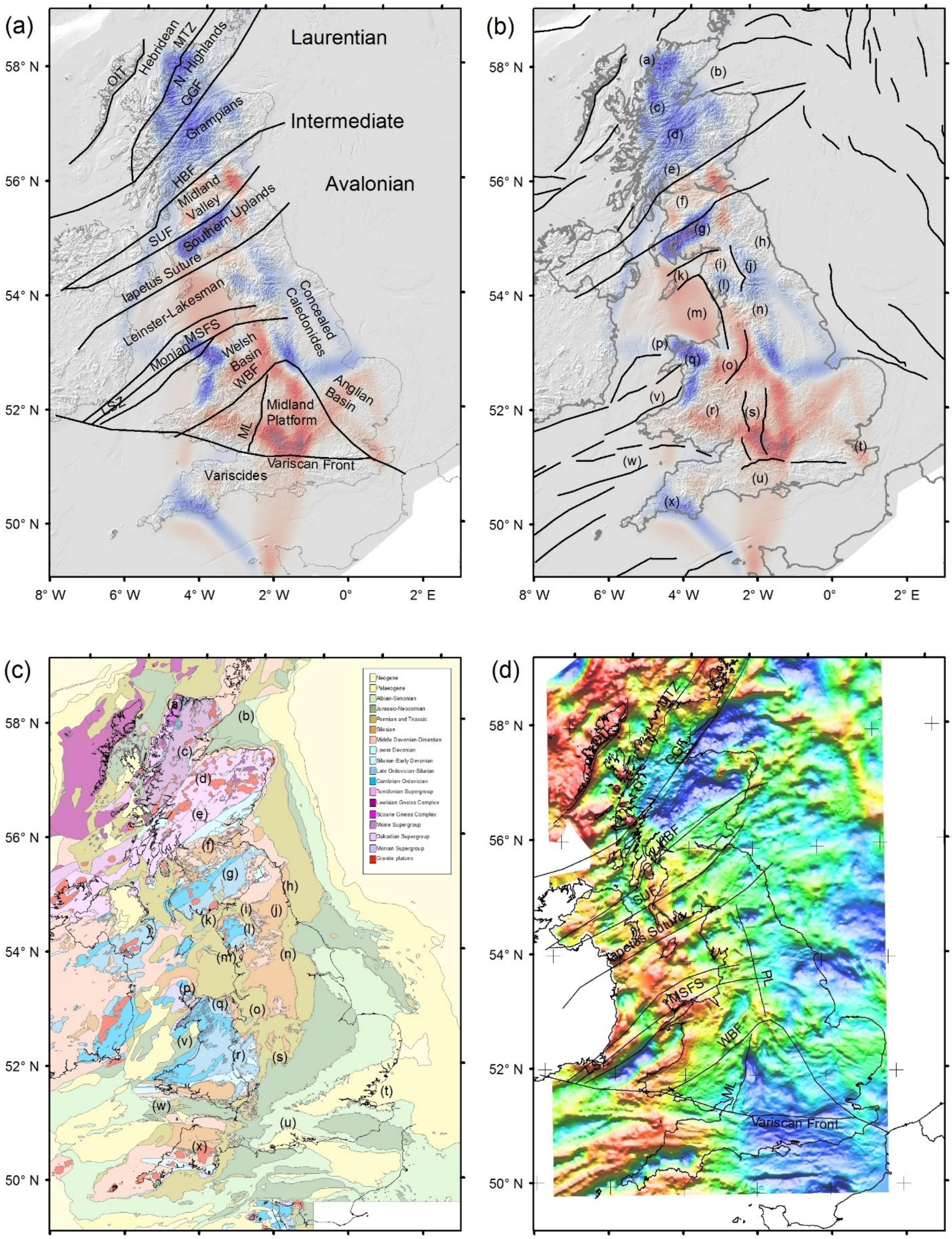
Recent research has shown that information about Earth structure between a pair of seismic stations can be extracted from cross-correlation of continuous background noise recorded at each station. This approach has been applied by Nicolson et al (2012) to produce the first surface wave group velocity maps of the British Isles using only ambient seismic noise.

Conventional 3D seismological models of the Earth are generally obtained from recordings of waves that have travelled to a given receiver from a single, known, energy source, for example, an earthquake. However, seismic waves propagate inside the Earth all the time, created by sources such as wind, ocean water movement, human-related activity and small-scale rock fracturing. Such waves are commonly regarded as "noise" by seismologists. However, these waves also reflect, refract and diffract from exactly the same heterogeneities as do waves from single active sources.

Recent advances in theory (e.g. Wapenaar, 2004) have shown that the cross correlation of the random wavefield between two seismic stations can provide an estimate of the Green's function between the stations. This has been confirmed using seismic data (Shapiro and Campillo, 2004). Nicolson et al (2012) have used data from broadband stations across Scotland to construct surface wave Green's Functions, which are then used to produce maps of the variation in surface wave velocities at different periods.

Nicolson (2011) constructs Green's functions from ambient noise data to produce the first surface wave group velocity maps of the UK for Rayleigh waves at different periods.

At short and intermediate periods, the maps show remarkable agreement with the major geological features of the British Isles including: terrane boundaries in Scotland; regions of late Palaeozoic basement uplift; areas of exposed late Proterozoic/early Palaeozoic rocks in southwest Scotland, northern England and north-west Wales; and, sedimentary basins formed during the Mesozoic such as the Irish Sea Basin, the Chester Basin, the Worcester Graben and the Wessex Basin. The maps also show a consistent low velocity anomaly in the region of the Midlands Platform, a Proterozoic crustal block in the English Midlands. At longer periods, which are sensitive to velocities in the lower crustal/upper mantle, the maps suggest that the depth of Moho beneath the British Isles decreases towards the north and west. Areas of fast velocity in the lower crust also coincide with areas thought to be associated with underplating of the lower crust such as Northern Ireland, the eastern Irish Sea and northwest Wales.

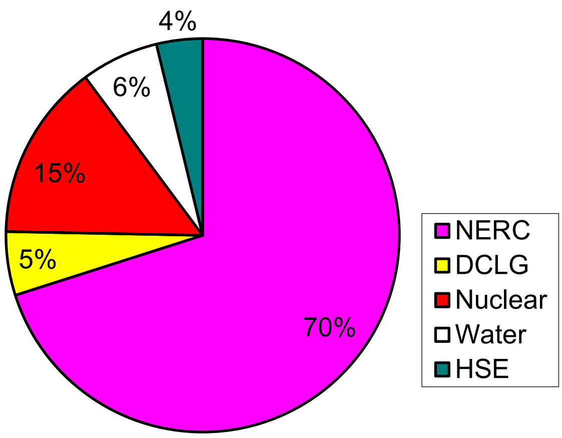


Five second Rayleigh wave group velocity maps alongside: (a) geological terrane boundaries; (b) areas of relative uplift and subsidence; (c) simplified surface geology and (d) regional gravity anomaly map. Solid black lines in (a) represent the major tectonic boundaries and fault structures. Solid black lines in (b) represent major basin bounding faults. Annotation on (b) and (c) is as follows: (a) Lewisian Complex; (b) Moray Firth Basin; (c) Moine Group; (d) Grampian Group; (e) Dalradian Group; (f) Midland Valley; (g) Southern Uplands; (h) Northumbria Basin; (i) Vale of Eden; (j) Alston Block; (k) Solway Firth Basin; (l) Lake District; (m) Irish Sea Basin; (n) Pennines; (o) Cheshire Basin; (p) Monian Group; (q) Snowdonia; (r) Welsh Massif; (s) Worcester Graben; (t) London Basin; (u) Wessex-Weald Basin; (v) Cardigan Bay; (w) Bristol Channel Basin; (x) Cornubian Massif.

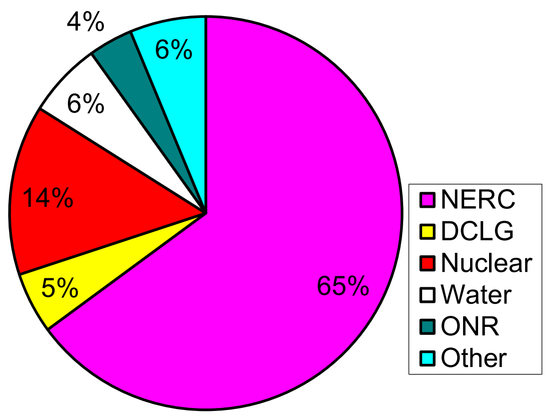
Funding and Expenditure

In 2012-2013 the project received a total of £603k from NERC. Some of this was won from specific funding calls. This was used to purchase spare hardware for the monitoring network. This was matched by a total contribution of £258k from the customer group drawn from industry, regulatory bodies and central and local government.

Funding Received 2012-2013



Funding Expected 2013-2014



The projected income for 2013-2014 is similar to that received in 2012-2013, albeit with a slight increase. The NERC contribution for 2013-2014 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 £314k. 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).

The report on the Global Historical Earthquake Archive (GHEA) owes much to the work of Paola Albini, Mario Locati and Andrea Rovida (INGV, Milan). Ron Harris and his team from Brigham Young University, Utah, kindly allowed the GHEA team access to unpublished research notes.

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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
Roger Musson	Historical earthquakes and seismic hazard
Susanne Sargeant	Seismic hazard and NERC Knowledge Exchange Fellow
Alice Walker	Observational seismology

Appendix 2 Publications

BGS Internal Reports

Baptie, B. 2012. Earthquake Monitoring 2011/2012, BGS Seismic Monitoring and Information Service, Twenty third Annual Report, British Geological Survey Open Report OR/12/092.

Galloway, D.D., 2013. Bulletin of British Earthquakes 2012. British Geological Survey Open Report, OR/13/054.

Luckett, R. and Baptie, B., 2012 Seismic monitoring of inundation of the Glencoe Hydro Scheme Reservoir. British Geological Survey Open Report, OR/12/062.

Shaw, R.P., Auton, C.A., Baptie, B., Brocklehurst, S., Dutton, M., Evans, D.J., Field, L.P., Gregory, S.P., Henderson, E., Hughes, A., Milodowski, A.E., Parkes, D., Rees, J.G., Small, J., Smith, N., Tye, A. and West, J.M., 2012. Potential natural changes and implications for a UK GDF. British Geological Survey Commercial Report CR/12/127N.

In addition, bulletins of seismic activity were produced monthly, up to six weeks in arrears for the Customer Group.

External Publications

Albini, P., Musson, R.M.W., Gomez Capera, A.A., Locati, M., Rovida, A., Stucchi, M. and Viganò, D., 2013. Global Historical Earthquake Archive and Catalogue (1000-1903). GEM Technical Report 2013-01.

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Musson, R. M.W., 2012. The effect of magnitude uncertainty on earthquake activity rates. Bulletin of the Seismological Society of America, 102 (6). 2771-2775.

Musson, R.M.W., 2012 An introduction to SSHAC. SECED Newsletter, 23 (4). 1-4.

Musson, R.M.W. and Cecić, I., 2012. Intensity and Intensity Scales - In: Bormann, P. (Ed.), New Manual of Seismological Observatory Practice 2 (NMSOP-2), Potsdam, Deutsches GeoForschungsZentrum GFZ.

Appendix 3 Publication Summaries

Global Historical Earthquake Archive and Catalogue (1000-1903).

Albini, P., Musson, R.M.W., Gomez Capera, A.A., Locati, M., Rovida, A., Stucchi, M. and Viganò, D., 2013.

The Global Historical Earthquake Archive (GHEA) provides a complete (so far as is possible) account of the global situation in historical seismology, with all existing studies of historical earthquakes collected together in a syncretised way, retrievable either by earthquake or region. It is truly a global survey of historical seismology as it exists at present. The Global Historical Earthquake Catalogue (GHEC) is a world catalogue of earthquakes for the period 1000-1903, with magnitude 7 Mw and over (less in some regions), derived from GHEA by a process of comparing the sets of parameters available for each earthquake and selecting the best-attested. This delivers to the Global Earthquake Model (GEM) the most comprehensive global historical catalogue of large earthquakes presently available, with the most reliable parameters selected, duplications and fakes removed, and in some cases, new earthquakes discovered.

UK Earthquake Monitoring 2011/2012

Baptie, B., 2012.

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 23rd year of the project, five new broadband seismograph stations were established, giving a total of 38 broadband stations. Real-time data from all broadband stations and nearly all other short period 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. We have also upgraded data acquisition hardware at most broadband stations to improve local storage and data communications.

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, 2012). In all reporting areas, scheduled targets have been met.

Seven papers have been published in peer-reviewed journals. A chapter was also published in a book. Two presentations were made at international conferences. Three BGS internal 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.

Bulletin of British Earthquakes 2013

Galloway, D.D., 2013

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 2013, listed in Tables 1 and 2. Maps showing seismic activity in 2013, 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).

Preese Hall Shale Gas Fracturing Review and Recommendations For Induced Seismic Mitigation.

Green, C., Styles, P. and Baptie, B., 2012.

In respect of future shale gas operations elsewhere in the UK, we recommend that seismic hazards should be assessed prior to proceeding with these operations. This should include: appropriate baseline seismic monitoring to establish background seismicity in the area of interest; characterisation of any possible active faults in the region using all available geological and geophysical data; application of suitable ground motion prediction models to assess the potential impact of any induced earthquakes.

Seismic monitoring of inundation of the Glencoe Hydro Scheme Reservoir.

Luckett, R. and Baptie, B., 2012.

Impoundment of reservoirs is known to sometimes cause earthquakes. At Glendoe in the Scottish Highlands the first large-scale hydro-electric power station to be built in the UK in almost 50 years was built in 2007/2008. In May 2008, a small network of seismometers was installed around the area due to be flooded at Glendoe to monitor any possible seismicity and these stations were maintained for a year after impoundment. Although a number of local earthquakes were recorded with good signal to noise ratios, no seismicity was recorded that can be attributed to the reservoir. This is perhaps because the dam is low, with a maximum water depth of 35m, whereas most reservoir induced seismicity has been observed at dams with water depths of over 100m.

The effect of magnitude uncertainty on earthquake activity rates.

Musson, R. M.W., 2012.

At present, any seismic hazard analyst seeking advice from the literature on how to handle uncertainty in magnitude values when calculating activity rates for seismic source zones may be alarmed to find two different viewpoints that apparently contradict one another, and that papers advocating one approach fail to mention the other, and vice versa. Superficially, it appears to be demonstrable that the uncertainty in earthquake magnitude either causes an overestimation of the true activity rate, or causes an underestimation. In this short note, it will be demonstrated that the resolution to the dichotomy depends not only on whether magnitude data have been converted, but also on how - a point not previously made. Various authors have proposed a correction factor to remedy the effect of uncertainty on activity rate, but if this is applied wrongly, the problem may be exacerbated. In practice, actual cases may be complex and difficult to resolve.

An Introduction to SSHAC.

Musson, R. M.W., 2012.

Many people with any connection to the subject of seismic hazard will by now have heard the acronym SSHAC, usually pronounced “shack”. There is, however, still a good deal of confusion, not helped by misinformation from some quarters, as to exactly what is entailed in a “SSHAC study”. Hence a short and somewhat simplified description may be timely.

Intensity and Intensity Scales

Musson, R.M.W. and Cecić, I., 2012.

Intensity can be defined as a classification of the strength of shaking at any place during an earthquake, in terms of its observed effects. The fact that it is essentially a classification, akin to the Beaufort Scale of wind speed, rather than a physical parameter, leads to some special conditions on its use. The word “macroseismic” is used to denote those effects of an earthquake that can be determined without the use of instruments. This includes intensity data but is not restricted to it. A list of places with associated intensity values is macroseismic data; so is the information that an earthquake was felt at a place, or caused damage there. The use of intensity scales is historically important because no instrumentation is necessary, and useful measurements of an earthquake can be made by an unequipped observer.

Potential natural changes and implications for a UK GDF.

Shaw, R.P., Auton, C.A., Baptie, B., Brocklehurst, S., Dutton, M., Evans, D.J., Field, L.P., Gregory, S.P., Henderson, E., Hughes, A., Milodowski, A.E., Parkes, D., Rees, J.G., Small, J., Smith, N., Tye, A. and West, J.M., 2012

A period of one million years following closure has been used by RWMD when considering the post-closure safety case for a geological disposal facility (GDF). It is during this period that evolution of the near-field and local geosphere as a result of GDF construction and operation will be at its most rapid and radioactivity of the emplaced waste will be at their highest levels. Significant effort has been spent internationally on identifying the many natural processes that may affect the evolution of the geosphere over this timescale and the contribution of those processes to GDF performance. The purpose of this report is to identify which processes are relevant to geosphere evolution in this time period around a generic GDF in the UK. Previous work has identified tectonic effects, climate change effects, uplift, subsidence, volcanism and diagenesis as key concerns. The potential impact of each of these processes on a generic UK GDF, constructed according to a multiple barrier concept and sited at a depth of between 200 and 1000 m in a suitable host rock, is outlined in the following sections: tectonic related uplift and subsidence; seismicity, tectonic history and volcanism; climate change and glaciation and weathering and erosion.