British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Earthquake Monitoring 2008/2009

BGS Seismic Monitoring and Information Service

Twentieth Annual Report

BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT OR/08/072

UK Earthquake Monitoring 2008/2009

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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 Department of Communities and Local Government (DCLG) with major financial input from the Natural Environment Research Council (NERC).

In the 20th year of the project, four new broadband seismograph stations were established, giving a total of twenty-three broadband stations. Real-time data from all broadband stations are being transferred directly to Edinburgh for archival and storage. Two strong motion accelerometers were installed on Jersey for monitoring the Queen’s Valley dam. Upgrade of the monitoring network remains our primary goal. We have purchased a further eight broadband sensors and high dynamic range digitisers as well as five strong motion accelerometers.

A temporary network of four seismograph stations was deployed around Glendoe to investigate induced seismicity that might result from the dam impoundment process for the Glendoe hydroelectric scheme.

The “Frontiers of Seismology” meeting, on 2-3 April 2009, at Our Dynamic Earth in Edinburgh was jointly organised by the British Geological Survey and the University of Edinburgh. More than 100 scientists from universities, research institutes and industry gathered to celebrate recent research achievements and look to the future of UK earthquake and exploration seismology.

Six papers have been published in peer-reviewed journals, with a further five articles published in non-refereed journals. Twenty-two presentations were made at international conferences. Six BGS internal reports were prepared along with five confidential reports. We have continued to collaborate widely with academic partners across the UK and overseas on a number of research initiatives.

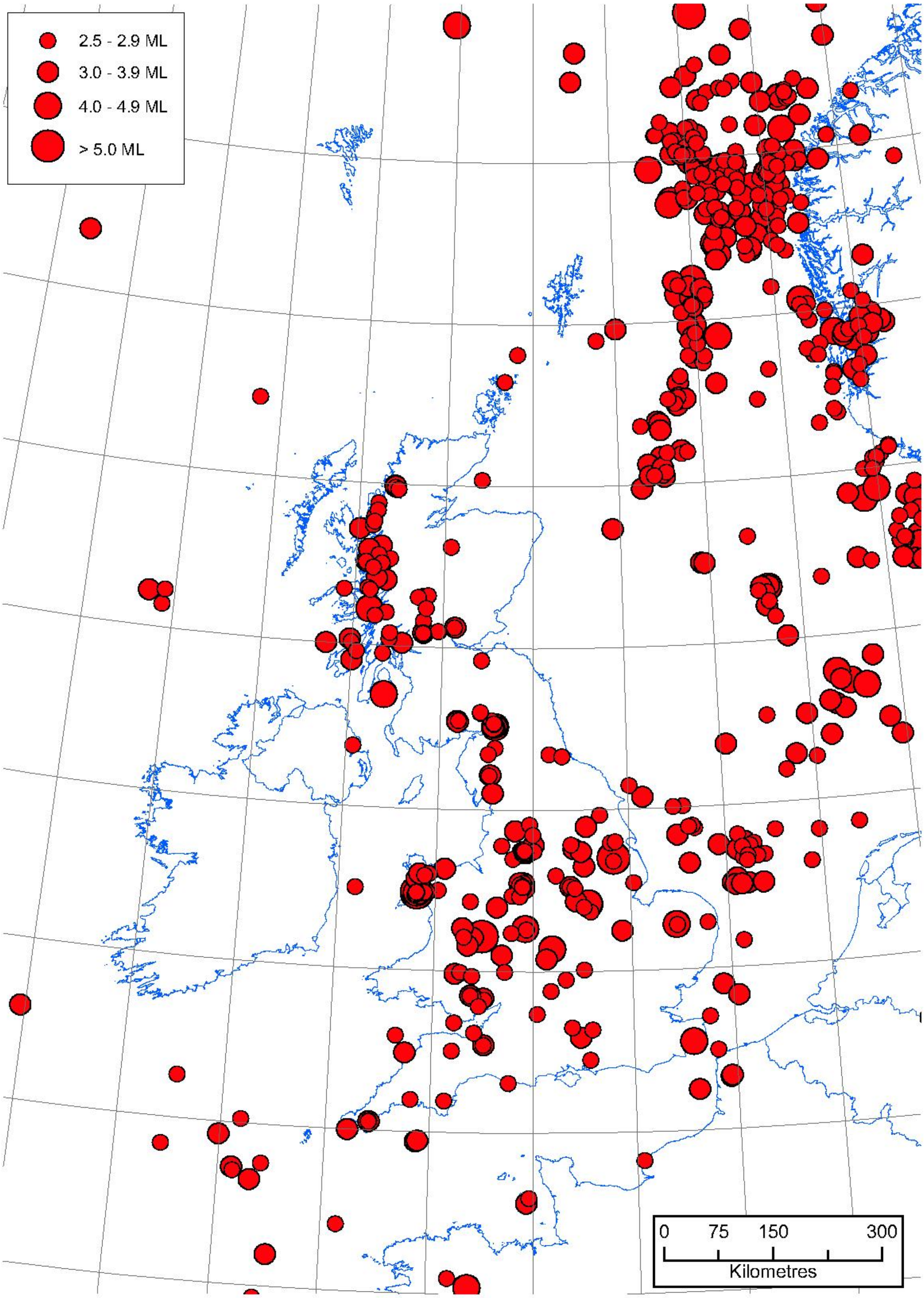
Introduction

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

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

In an average year, about 100 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 December 2008

Introduction

Monitoring Network

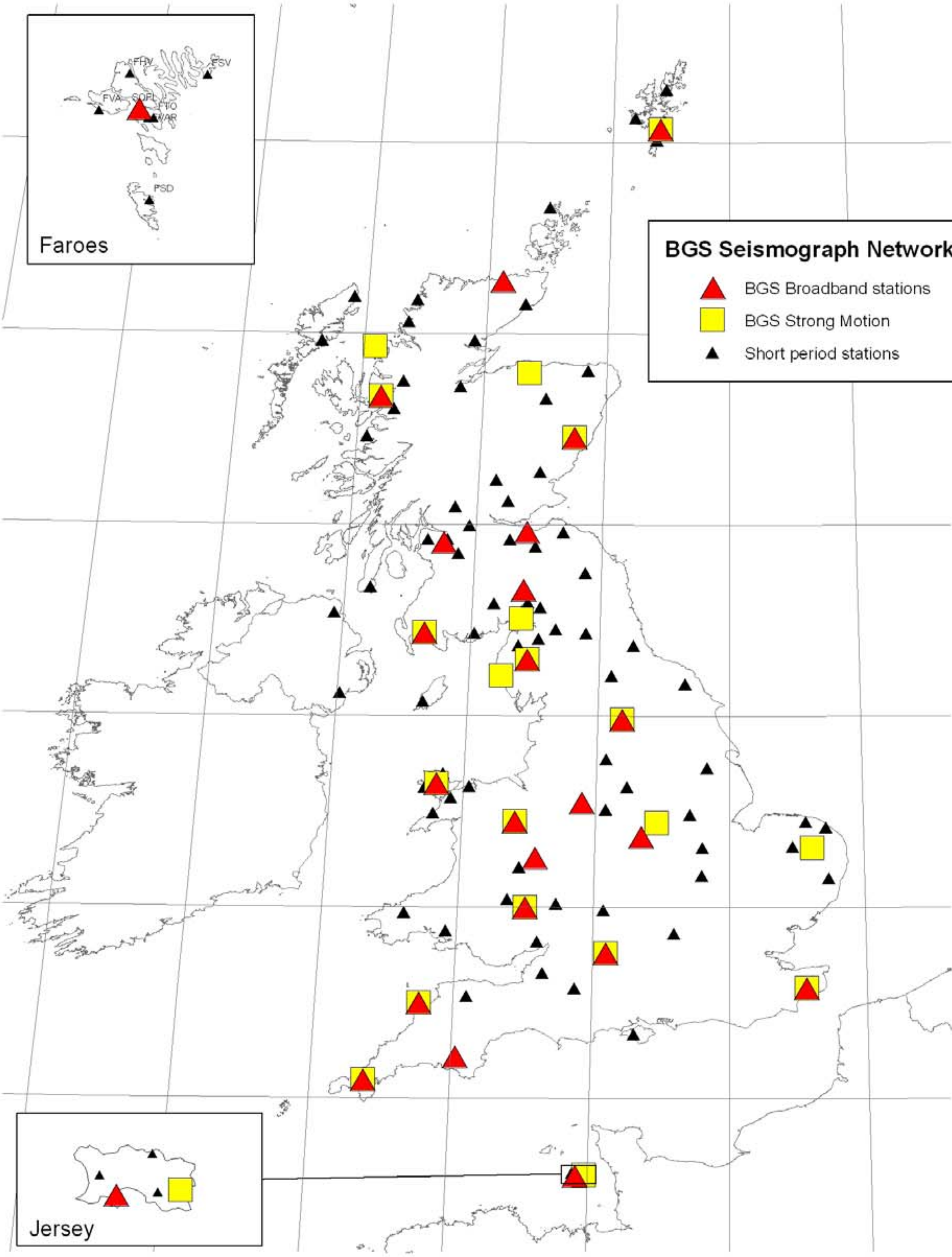
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late nineties, the number of stations reached its peak of 146 stations, with an average spacing of 70 km. We are now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



BGS seismograph stations, March 2009

Achievements

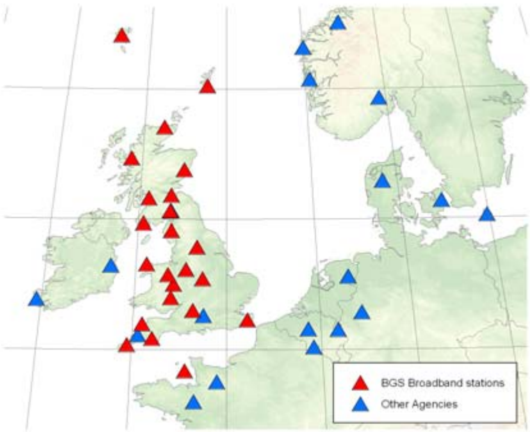
Network Development

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 five new broadband stations were installed at: Elham (Kent), Keswick (Cumbria), Foel Wylfa (North Wales) and Drumochty (Aberdeenshire). Continuous data from all four stations are transmitted in real-time to Edinburgh, where they are used for analysis and archived. This takes the total number of broadband stations operated by BGS to twenty-three.

Work is almost complete on new broadband stations in Lincolnshire and Caithness. In addition, we have carried out site surveys for new broadband stations at Comrie and Teeside.

Eight new broadband seismometers, along with high dynamic range data acquisition, were purchased during the year 2008-2009. These will be deployed either at existing or new stations as part of our network development programme. We also purchased five strong motion accelerometers that will remain on-scale up to 0.5g. These will be deployed alongside broadband instruments at a number of stations.



Broadband stations in northern Europe contributing to our near real-time detection and location capability.

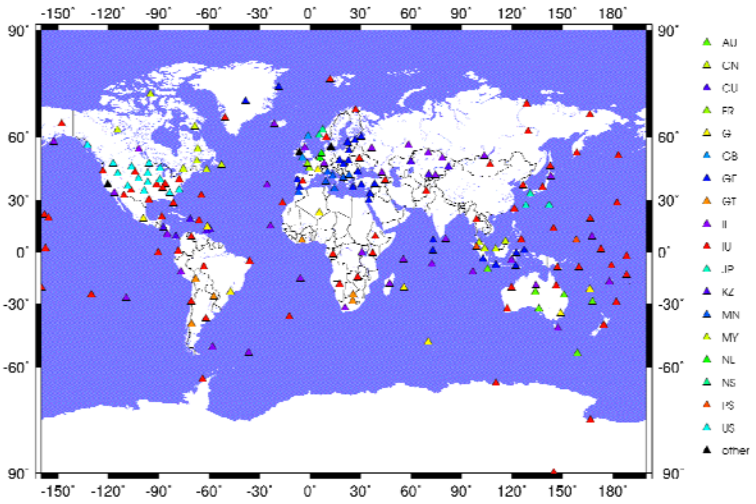
Two strong motion accelerometers were installed at the Queens Dam on Jersey with high dynamic range data acquisition and high speed telemetry to Edinburgh.

We also maintain a pool of seismometers that can be rapidly deployed for studying aftershock sequences, earthquake swarms and specific studies. These instruments were deployed to capture aftershocks following the recent earthquakes at Folkestone and Market Rasen. In the case of Market Rasen, four instruments were deployed within 48 hours of the mainshock, and successfully recorded a number of aftershocks in the following months.

We have increased the flow of real-time data from seismic stations operated by European partner agencies into our near real-time processing. These include data from Belgium, Denmark, France, Ireland, the Netherlands and Norway. The use of these data greatly improves our detection capability in offshore areas.

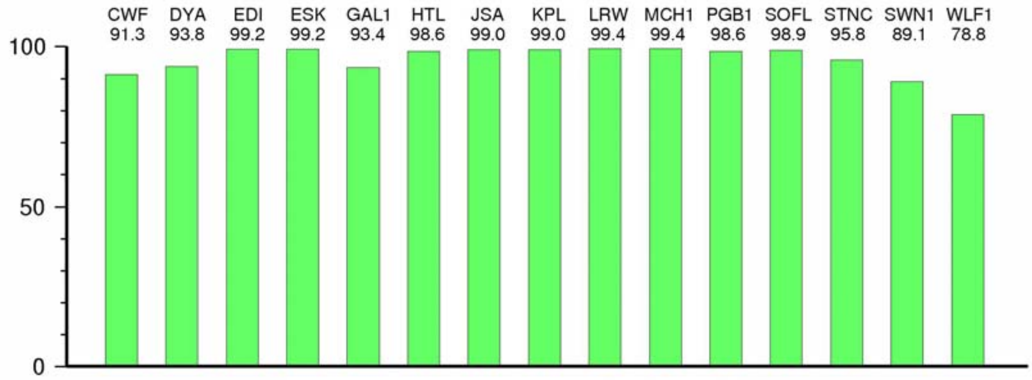
We are continuing to use *EarthWorm* software (developed by the US Geological Survey and contributed to by BGS) as a central part of our seismic data acquisition and processing. *EarthWorm* consists of a set of modules that perform tasks, such as data acquisition, phase picking, archival etc.

In the last year we have implemented a new alert system to provide rapid notification of potentially damaging earthquakes anywhere in the world. Our seismologists now receive alerts within minutes of any earthquake with a magnitude greater than 7. The alert is sent by a real-time acquisition and analysis system called *EarlyBird* which has been installed, tuned and tested in Edinburgh for possible future use in a tsunami warning system. The software was developed at the West Coast/Alaska Tsunami Warning Center and has been in use there, as well as at other centres worldwide, for many years. *EarlyBird* automatically locates earthquakes, as well as calculating magnitudes and source mechanisms, using data from over 200 stations throughout the world that are made available in near real time by institutions such as IRIS and ORFEUS as well as through direct data sharing arrangements between the BGS and other seismological observatories. Waveforms are continuously filtered, picked and associated with possible earthquakes and whenever a large enough event has been confirmed a warning message is sent by both E-mail and SMS.



Seismic stations contributing to the EarlyBird real-time processing system used to alert staff to large global earthquakes.

Continuous data from all our broadband stations are now online within the BGS storage area network. The completeness of these data can be easily checked to gain an accurate picture of network performance. In general, we find that the data from most broadband stations are over 92% complete. Data losses result from failure of outstation hardware, communications problems, or failure of central data processing. Station WLF1 on Anglesey suffered a number of problems in 2008-2009 including equipment and communications failures, which resulted in significant loss of data. 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.



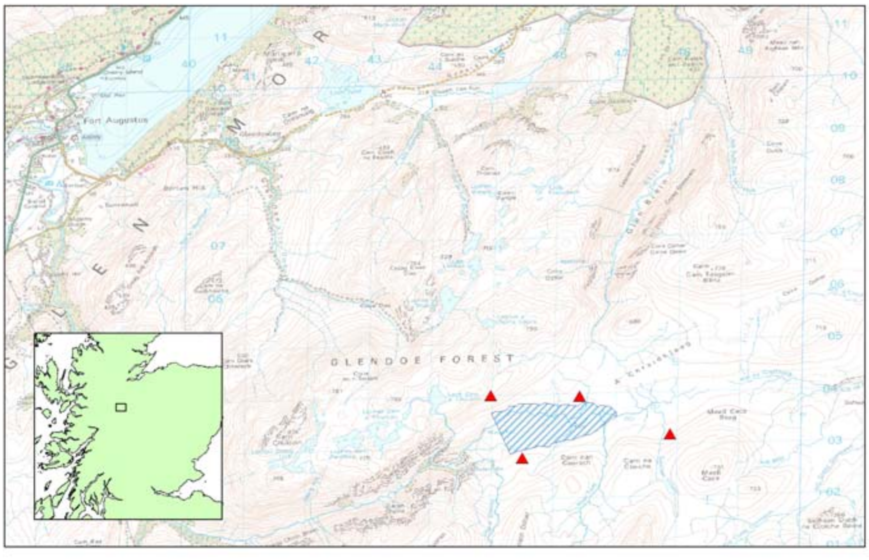
Data completeness for selected broadband stations for April 2008- March 2009

Achievements

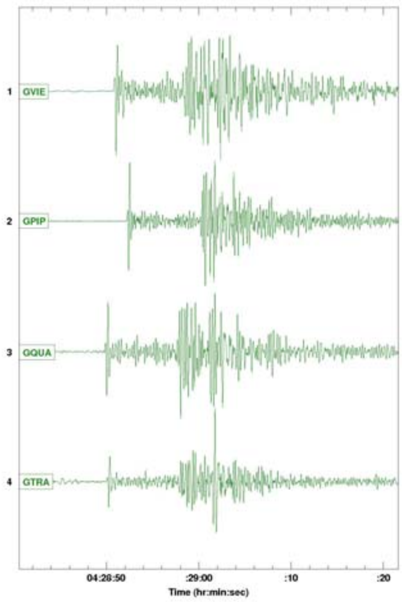
Glendoe Monitoring

It is well known that the dam impoundment process can result in induced seismicity, depending on water height and local tectonics. The Glendoe hydro-electric scheme involved the construction of the largest reservoir in Britain for many years. The dam is over 900 m long and 35 m deep at its highest point.

The Scottish and Southern Energy Glendoe Hydro Scheme is the first large-scale conventional hydro electric station to be built in Scotland for almost 50 years. A small array was deployed during 2008 to monitor possible induced seismicity associated with the filling of the new reservoir, or to prove the absence of any new earthquake activity. A 960 m dam was built across the river Tarff 600 m above Loch Ness and 16 million cubic metres of water are now stored there. It is well established that large dams can trigger earthquakes (Talwani, 1997). This is generally thought to be because increased water pressure in micro-cracks lubricates faults which are already under tectonic strain. Such induced seismicity usually occurs soon (between a few days and a year) after the reservoir reaches its maximum depth (Simpson, 1988). In May 2008 four temporary seismic stations were installed around the area due to be flooded at Glendoe. These had been recording for several months by the time the dam was completed in September and inundation started. The reservoir was full by early December 2008 when power generation began. Data from the instruments has been generally satisfactory and several local earthquakes have been recorded with good signal to noise ratios. However, so far no seismicity has been recorded that can be attributed to the reservoir. This is perhaps because the dam is low, with a maximum height of 35m for only a small proportion of its length, where the previous river valley was. Most reservoir induced seismicity has been observed for dams over 100 m in height.



Map of Glendoe showing reservoir (shaded) and seismic monitoring stations (red triangles)



Seismograms of the a magnitude 3.5 M_L earthquake near Fort William on 10 October 2008 recorded on the Glendoe stations

Before impoundment

After impoundment

Information Dissemination

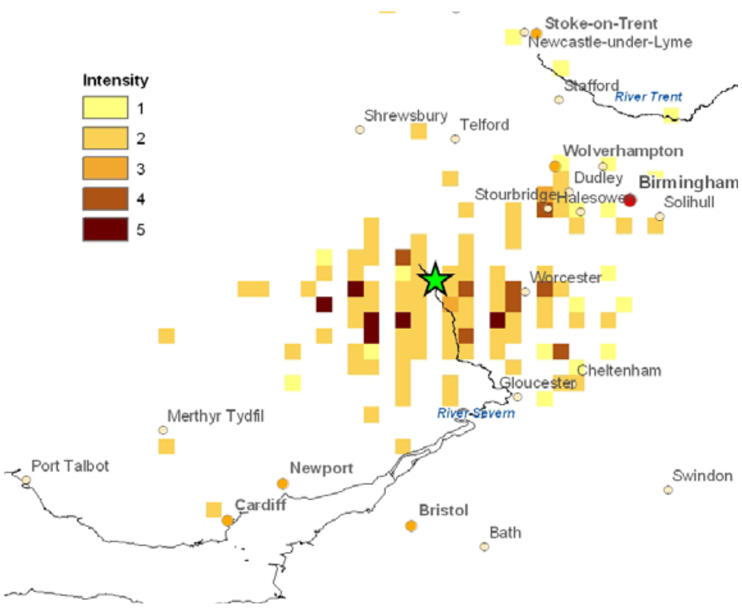
It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received notification by e-mail whenever an event was felt or heard by more than two individuals.

Notifications were issued for 27 UK events within the reporting period, two of which were of a suspected sonic origin and one was for an explosion, and for 28 global 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, one enquiry was received from Heysham Nuclear Power Station after alarms triggered, and a response was given within 15 minutes.

An up-to-date catalogue of recent events continues to be available on the Seismology web pages. This is updated whenever a new event is located. Our automatic macroseismic processing system 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 following both the Bromyard and Fort William earthquake earthquakes.

Data from the returned 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 on CD, the revised annual Bulletin of British Earthquakes within six months of the end of a calendar year. For 2008, it was issued in June 2009.



Response to online macroseismic survey for the Bromyard earthquake

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 exchange data with European and world agencies.

A PhD student at Edinburgh University, funded partially by BGS, is using ambient seismic noise recorded on broadband stations across the UK to extract information on Earth structure.

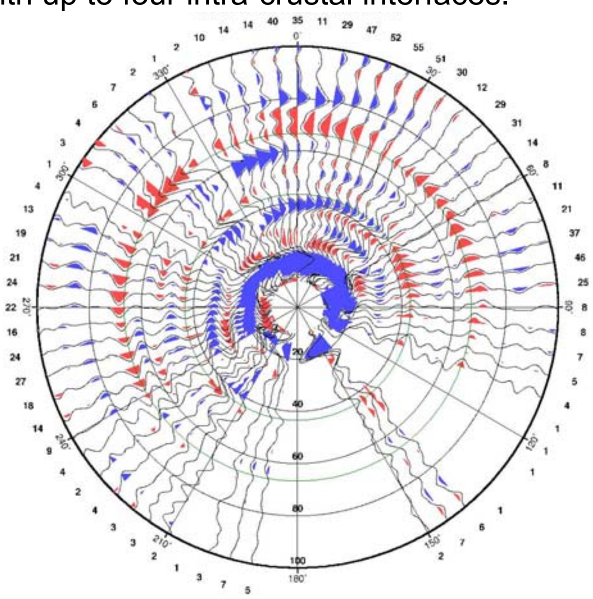
Conventional 3D seismological models of the Earth are generally obtained from recordings of waves that have travelled to a given receiver from a single, known, energy source, for example an earthquake. However, countless other seismic waves propagate inside the Earth all of the time, created by sources 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.

The first part of this project is the application of these new techniques to continuously recorded background seismic noise data to construct surface wave seismograms. Velocity information will be extracted from the constructed surface waves, which can be inverted to produce tomographic maps of the crust and upper mantle of the UK and North Sea area.

A BGS CASE student at the University of Cambridge is using recordings of distant earthquakes to image upper mantle structure under the UK and investigate causes of regional uplift of the British Isles. During Cenozoic times permanent uplift was generated by magmatic underplating when the North Atlantic ocean opened over the Iceland plume. However, beneath the British Isles the existence of magmatic underplating is debated and its spatial extent is poorly known.

In collaboration with the British Geological Survey 27 broadband seismometers have been installed across the British Isles, with data for a further 15 stations available from other agencies. Teleseismic arrivals recorded at each station have been used to calculate receiver functions allowing a dense study of both the crust and mantle transition zone discontinuities. This method allows the thickness and lateral extent of underplating to be determined.

Initial results yield Moho depths of ~32 km with up to four intra-crustal interfaces.



Receiver functions at ESK stacked in 10 deg bins and plotted radially from 20 to 100 seconds with 2 sigma error bounds above/below zero shown in red/blue (Davies *et al*, 2009)

Within the mantle, conversions due to the 410 and 660 km discontinuities are observed at each station and the 520 km discontinuity is detected patchily. The 660 km discontinuity shows varied signals with asymmetric and multiple peaks, even under individual seismometers. The average time between the 410 and 660 arrivals is equal to the global average of 24 seconds. However, a thinner mantle transition zone is visible beneath Scotland and southern England.

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

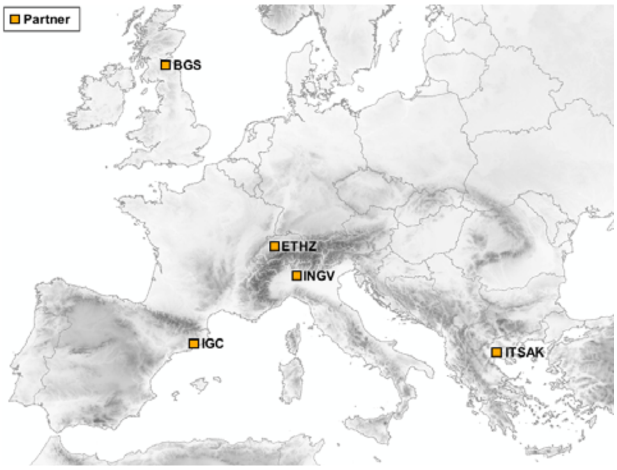
BGS together with INGV, Milan, and other institutes are working together within the NERIES project to produce a definitive database of historical intensity observations from larger European earthquakes.

BGS staff have been included in the participatory peer review panel for a major (SSHAC Level 3) seismic hazard study in South Africa.

BGS are working with INGV and ETHZ on the development of the project proposals “Tech-Tonikas” and “SHARE”, respectively. These are intended for submission to the EU FP7 project call.

Development in co-operation with the University of Bergen on seismic analysis (SEISAN) and network automation (SEISNET) software has continued.

BGS assisted with the ‘International Training Course on Seismology, Seismic Data Analysis, Hazard Assessment and Risk Mitigation’ organised by the German Research Centre for Geosciences (GFZ), Potsdam.



Partners working on NERIES NA4: Distributed archive of historical earthquake data

BGS data is exchanged regularly with European and world agencies to help improve source parameters for earthquakes outside the UK. As a *quid pro quo*, BGS receives data for UK earthquakes and world events of relevance to the UK, recorded by many other agencies and institutions. Phase data for global and regional earthquakes are distributed to the European-Mediterranean Seismological Centre (EMSC) to assist with relocation of regional earthquakes and rapid determination of source parameters for destructive earthquakes. BGS data for 53 events were supplied to the EMSC. *EarlyBird* automatic alerts are also sent to the EMSC. A number of events that had been misidentified as earthquakes were reassigned as explosions using our data. Phase data for global earthquakes are sent to the National Earthquake Information Centre (NEIC) at the USGS. Phase data are also made available to the International Seismological Centre, an agency providing definitive information on earthquake hypocentres. 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, in near real-time.

Achievements

Frontiers of Seismology

A two day meeting, “Frontiers of Seismology”, jointly organised by the British Geological Survey and the University of Edinburgh on 2-3 April 2009, at Our Dynamic Earth in Edinburgh. More than 100 scientists from universities, research institutes and industry gathered to celebrate recent research achievements and look to the future of UK earthquake and exploration seismology.

The UK is home to a vibrant and diverse seismological research community investigating everything from seismic wave propagation in the deep earth to major subduction zone earthquakes. However, it had been many years since there has been a meeting to discuss advances in seismological research by scientists in Britain. The meeting on ‘Frontiers of Seismology’ was held on 2-3 April 2009 in Edinburgh at the ‘Dynamic Earth’, and jointly organised by the British Geological Survey and the University of Edinburgh to bring together these diverse groups. The meeting was also intended as a forum to bridge boundaries between communities, for example between industrial and academic researchers, and scientists concerned with either engineering, social or natural aspects of earthquakes.

It was well attended by 105 participants mostly from the UK coming from universities, research centres and industry. The NERC theme leader for ‘Natural Hazards’ was present to discuss funding possibilities under the theme action plan.

The programme for the two days was divided into ‘Earth Imaging’ and ‘Earth Dynamics’. Exciting science was presented in a total of 32 talks and 30 posters from a broad range of topics. Feedback on the meeting was generally very positive in particular on the science presented and the venue, with general agreement that the meeting should be repeated every two years.

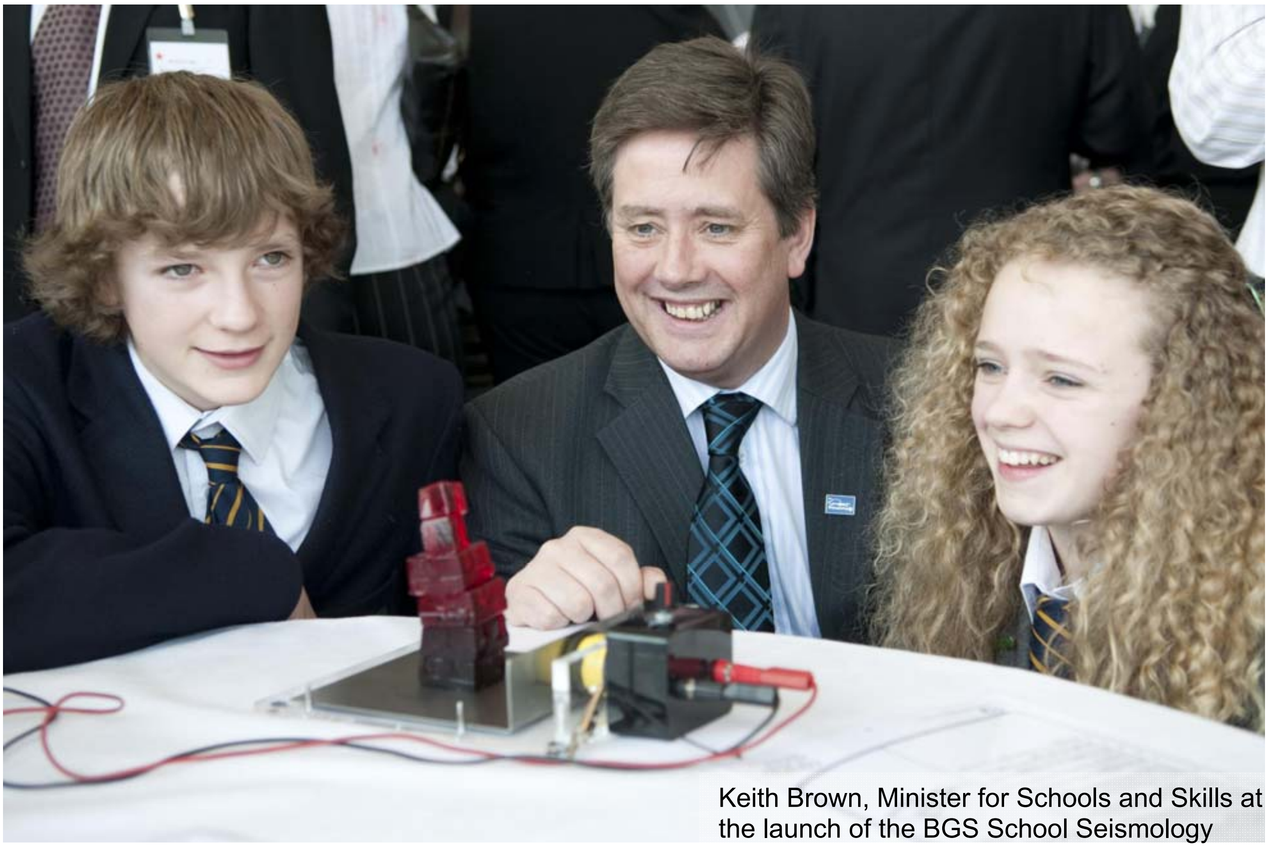
Achievements

Public Understanding of Science

An important part of the BGS mission is to disseminate information to the community and promote the public understanding of science. Our “School Seismology” project has aimed to support the teaching of seismology in schools and stimulate interest in Earth Science.

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 real scientific data and help students conduct investigations using their own data.

In 2008-2009 the BGS ran six training workshops for teachers in partnership with Imperial College (two workshops), Plymouth University, Keele University, Leeds University and University College London. This brings the total number of teachers trained and provided with seismometers to 160 in the UK. Most of the teachers attending workshops in 2008-2009 were provided with free seismometer



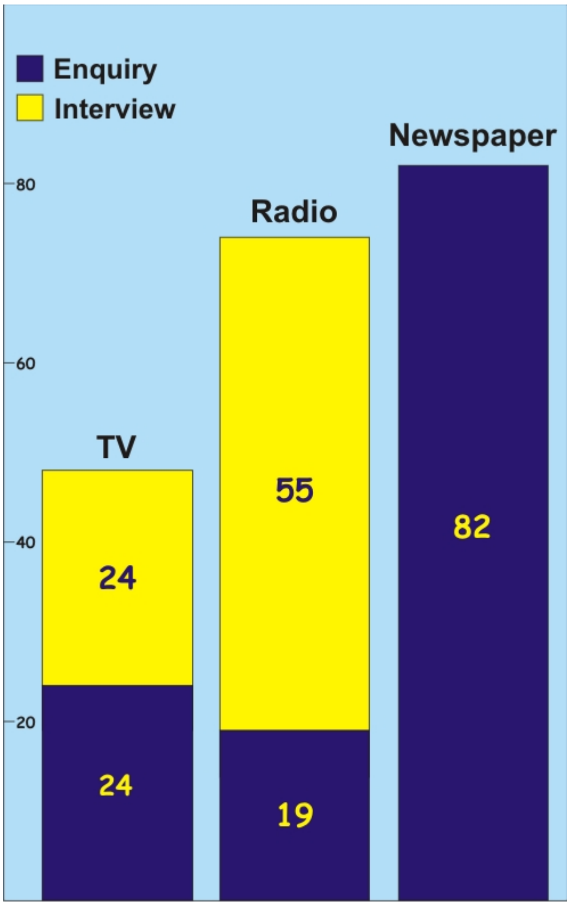
Keith Brown, Minister for Schools and Skills at the launch of the BGS School Seismology Project in Scotland systems by the university partner outreach programmes.

Also during 2008-2009 the UKSSP managed to secure funding from the Scottish Oil Club (£10K) which has helped pay for the launch of the UKSSP in Scotland. The Petroleum Exploration Society of Great Britain also provided £25K to the project. This money has been distributed to ten UK universities (seven in England, one in Wales and two in Scotland) to support provision of free seismometers to schools in 2009-2010.

The UKSSP has been building on its international links and has put in place a framework with school seismology projects in Ireland and the USA to share data recorded by schools in the three countries. In addition links are being made with school seismology projects in Europe and Africa.

The BGS Open Day attracted 850 visitors with many of them visiting the interactive earthquake display. A further 167 school pupils from 9 different schools visited during the following Schools Week.

The seismology web site continues to be widely accessed, with over 510,000 visitors logged in the year (over 10 million hits). Significant peaks (10,000 more than the monthly average) were observed following the Sichuan earthquake (May 2008), the Glenfinnan and Bromyard earthquakes (October 2008) and the Folkestone earthquake (March 2009).



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 2008-2009, 656 enquiries were answered. Some 204 of these were from the media, including 122 for TV and radio broadcasts following significant earthquakes. The broadcasting enquiries led to 24 TV and 55 radio interviews.

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 2008, published and distributed in June 2008 (Galloway, 2009).

There were 104 local earthquakes located by the monitoring network during the year, with 31 having magnitudes of 2.0 M_L or greater, and six having magnitudes of 3.0 M_L or greater. Six events with a magnitude of 2.0 M_L or greater were reported felt, together with a further six smaller ones, bringing the total to twelve felt earthquakes in 2008.

A magnitude 3.5 M_L earthquake occurred near Bromyard, Herefordshire at 18:06 UTC on 26 October 2008. Over 400 of the people who completed our online macroseismic survey felt the earthquake. The strength of the shaking was moderate, enough to make furniture shake and windows and crockery rattle. Some reports indicate that people were woken from sleep and a few were frightened, indicating an intensity of at least 5 EMS.

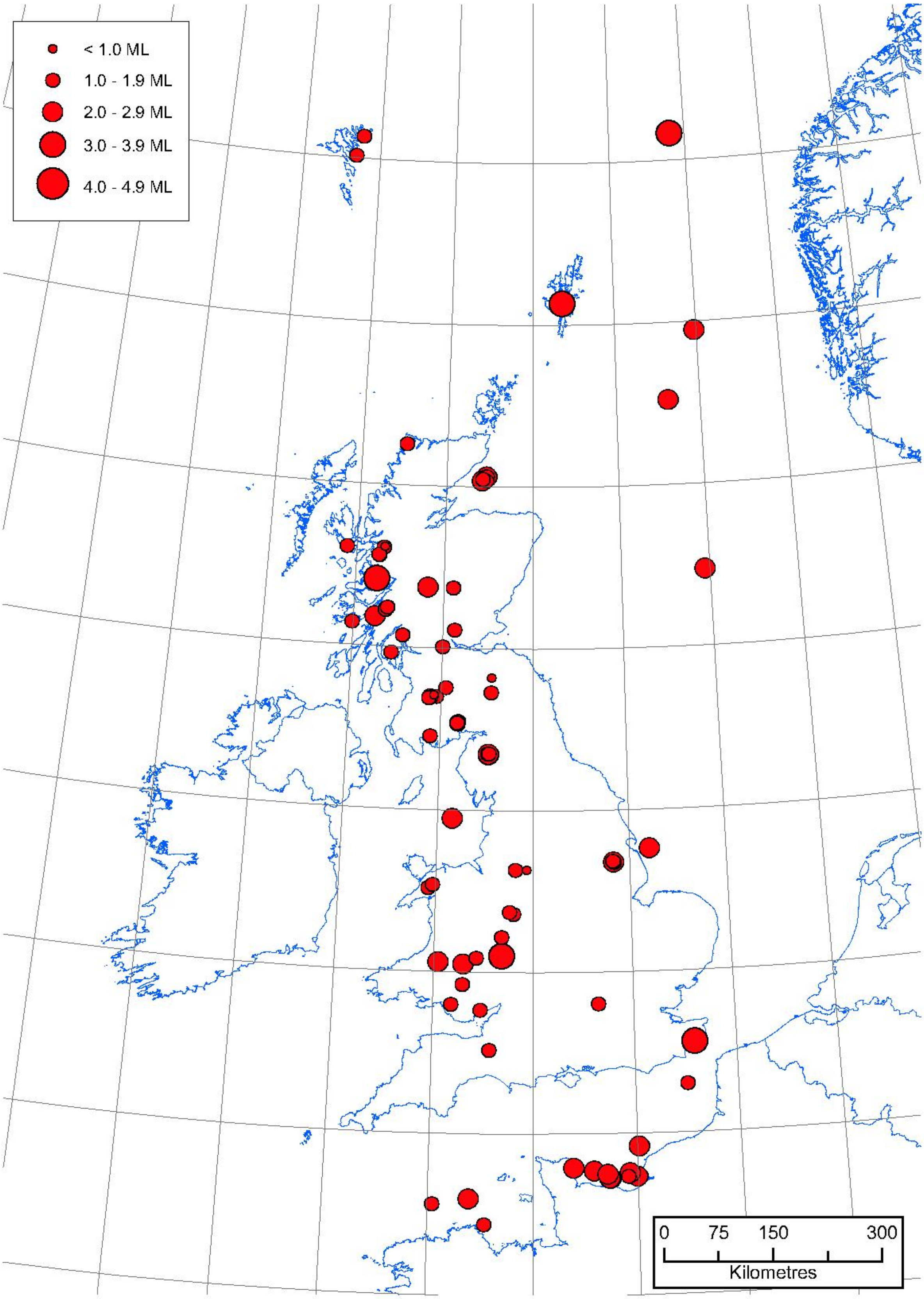
On 10 October 2008 at 04:28 UTC a magnitude 3.5 M_L earthquake occurred near Fort William, Highlands. The earthquake was felt by over 200 people. Again, the strength of the shaking was moderate, with reports indicating that people were woken from their sleep.

A magnitude 3.3 M_L earthquake in the Shetland Isles on 15 January 2009 was widely felt. This was the largest earthquake to strike this area since a magnitude 3.5 earthquake on 12 October 2002, approximately 85 km to the southeast. The Shetland Isles are low in seismic activity with few events above 2 M_L. The only earthquake of note to have occurred on the mainland of Shetland Isles was a magnitude 2.0 on the island of Unst in 1886.

A magnitude of 3.0 M_L earthquake occurred directly under Folkestone on 3 March 2009. The earthquake was felt by many residents of Folkestone and the surrounding area. The earthquake was around 200 times smaller than the magnitude 4.3 earthquake that struck Folkestone on 28 April 2007, causing some damage.

The largest offshore earthquake occurred in the Norwegian Sea on 14 October, with a magnitude of 3.9 M_L. It was located approximately 275 km northeast of Lerwick, Shetland Islands. A further five events occurred in the North Sea and surrounding waters during the year, with magnitudes between 2.2 and 3.1 M_L.

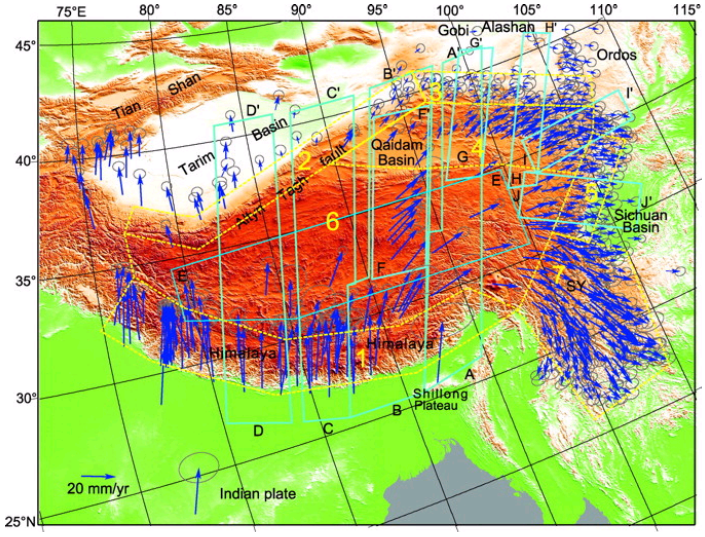
The UK monitoring network also detects large earthquakes from around the world, depending on the event size and epicentral distance. Recordings of such earthquakes can be used to provide valuable information on the properties of the crust and upper mantle under the UK, which, in turn, helps to improve location capabilities for local earthquakes. During the period April 2008 to March 2009, a total of 510 teleseismic earthquakes were detected and analysed.



Epicentres of all UK earthquakes detected in 2008.

Seismic Activity

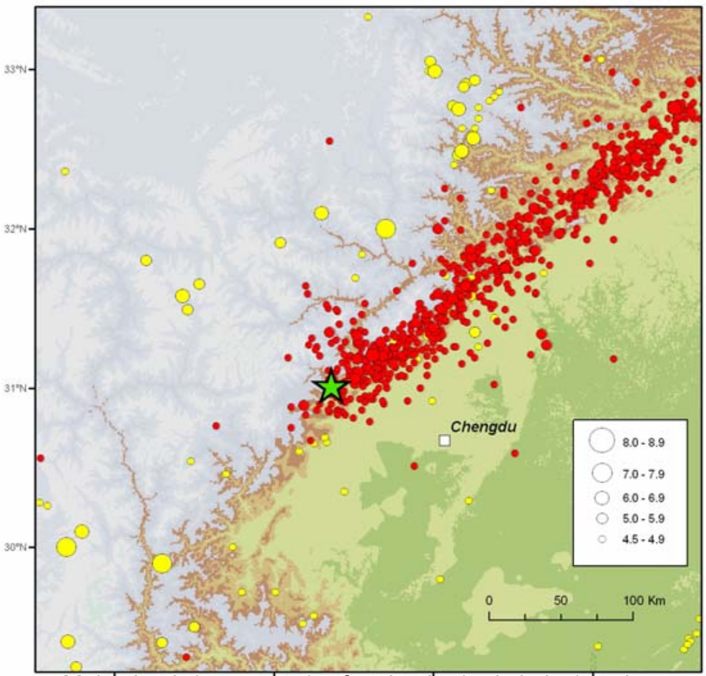
The Wenchuan Earthquake 12 May 2008



Global positioning system velocities (mm/yr) in and around Tibetan Plateau (Zhang *et al*, 2004)

The magnitude 7.9 earthquake of May 12, 2008 in Sichuan was the most devastating earthquake to strike China in over thirty years and resulted in over 70,000 deaths and left more than 4.8 million homeless. The earthquake has also drawn direct attention to the complex tectonic and geologic history of the Longmen Shan and eastern margin of the Tibetan Plateau.

The earthquake occurred on the Yingxiu-Beichuan fault, at the eastern margin of the Sichuan Basin. Fault plane solutions obtained from seismic data show that the earthquake took place on a thrust fault with the rocks to the northwest of the fault being thrust up and over the rocks to the southeast. Hundreds of aftershocks map out the main-shock fault plane, which

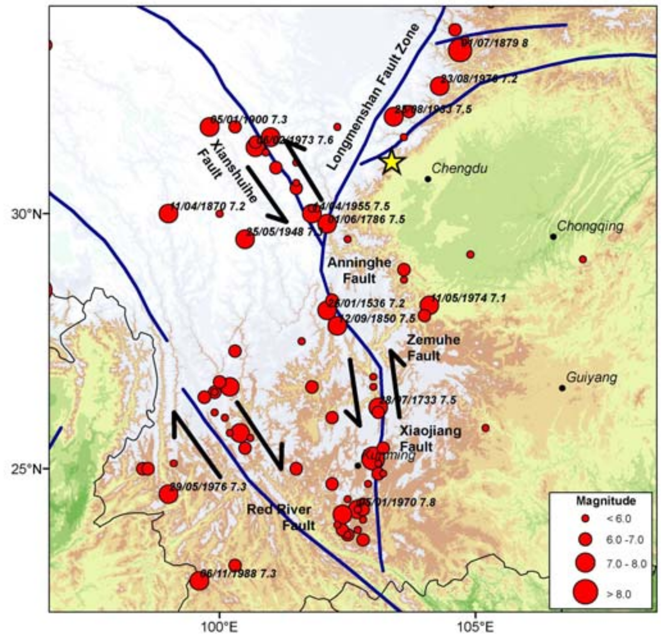


Main shock (green star), aftershocks (red circles) and historical seismicity (yellow circles).

extended from the epicentre in the southwest over 300 km to the northeast, taking over two minutes to rupture. The maximum amount of slip was around nine metres. Observers have been able to map the rupture at the surface for over 200 km, with a vertical uplfit of many metres in places.

On a continental scale, the seismicity of central and eastern Asia is a result of northward convergence of the India plate against the Eurasia plate with a velocity of about 50 mm/y. This can be clearly seen in global positioning system (GPS) velocities (mm/yr) in and around the Tibetan plateau with respect to a stable Eurasia (Zhang et al, 2004). The convergence of the two plates results in the uplift of the Asian highlands and by the motion of crustal material to the east away from the uplifted Tibetan Plateau.

The dramatic relief of the Longmenshan (Dragon’s Gate) mountain range, with topography rising to over 7,000 m, is similar to the Himalayas in relief and typical of rapid convergence within the crust (Kirby *et al.*, 2008). However, GPS measurements show that active convergence is much smaller than might be expected. This might lead one to



believe that strain accumulation and therefore seismic hazard are lower that other parts of the region. Zhang *et al.* (2004) explain this by suggesting that the rigid upper crust is detatched from a weaker lower crust and lithosphere, such that there is continued extrusion of a viscous lithosphere from west to east below the plateau into the Longmenshan, where it is impeded by the rigid Sichuan basin. Crustal thickening is then driven by flow and deformation in the lower crust.

A simplified geology of the eastern Tibetan Plateau shows a number of major fault systems and considerable historical seismicity. The large strike-slip fault systems to the south and east of the Sichuan Basin are very active, resulting in many earthquakes. However, there are fewer earthquakes in the Longmen Shan than on some of the other fault zones around the Tibetan Plateau. In August 1933 an earthquake with a magnitude of 7.5 occurred near Diexi, about 90 km notheast of the Sichuan earthquake. This destroyed the town of Diexi and surrounding villages, and caused many landslides, some of which dammed the rivers. Approximately 9,000 people died, though damage in Chengdu was slight. It was felt as far away as Xian.

A number of the faults at the margin of the Longmenshan with the Sichuan basin had recently been studied by Densmore *et al.* (2007), who concluded that some of these had been active in the last 10,000 years and could present a significant seismic hazard.


Secondary School in Yin Xiu

Scientific Objectives

Modelling Ground Motion from the Folkestone and Market Rasen Earthquakes

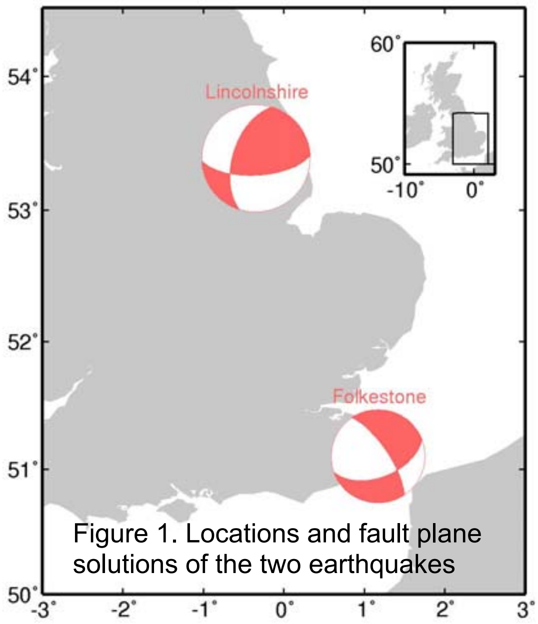


Figure 1. Locations and fault plane solutions of the two earthquakes

In areas of low seismicity like the UK, there is generally a lack of strong motion observations. This presents a problem in seismic hazard studies, which rely on ground motion relationships. One way to overcome this it to apply ground motion modelling based on expected earthquake source parameters. Here, we use a stochastic modelling approach to obtain ground motion estimates.

We used the stochastic approach (Boore, 1983) and the *SMSIM* software (Boore, 2005) to compute ground motion estimates using the source parameters for two recent British earthquakes. The Folkestone earthquake occurred on 28 April 2007 with a local magnitude 4.3 M_L. The earthquake was shallow with a depth of 5 km. The Market Rasen earthquake of 27 February 2008 was located about 275 km northwest of Folkestone and had a local magnitude of 5.2 M_L. This earthquake had a source depth of 20 km. It was very widely felt throughout the UK in contrast to the Folkestone earthquake which was felt only locally. This difference is explained both by the Market Rasen earthquake being larger and deeper. Source mechanisms for both earthquakes were determined by moment tensor inversion (Figure 1).

We determined the seismic moment, and the stress drop from the corner frequency of the two main-shocks by modelling the source displacement spectra (Ottemöller and Havskov, 1999). The modelling requires knowledge of the path attenuation and geometric spreading, but also the site or near-surface attenuation. We found stress drops of 30 and 344 bars for the Folkestone and Market Rasen earthquakes, respectively. As the excitation of ground acceleration is controlled by the stress drop we expect to see differences when comparing to the empirical ground motion relationships which correspond to a mean stress drop. We also tested whether we can compute the ground motion values using the stochastic approach based on our source and attenuation models.

In the stochastic modelling, a white noise time domain signal is generated with zero mean and on average unit spectral amplitude. This signal is then shaped by multiplying with a frequency dependent source function. The PGA values are then calculated after transformation to the time domain. The modelling result is computed as average from a number of runs (we use 50). The results from this modelling in comparison to the observed data and the empirical relationship of Campbell and Bozorgnia (2006) are shown in Figure 2.

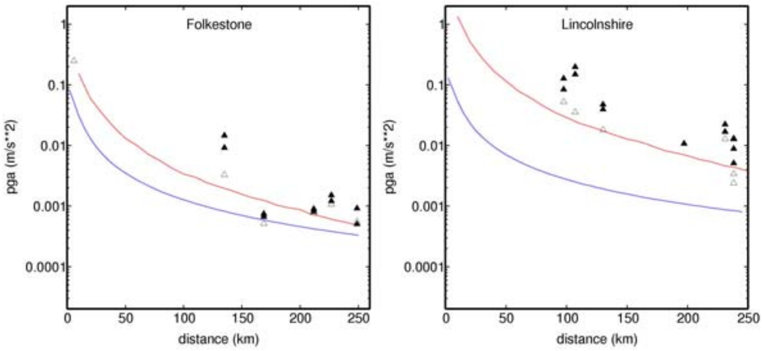


Figure 2. Observed PGA (filled triangles for horizontal and open triangles for the vertical) compared with results from stochastic modelling (red). Also shown are empirical ground motions (blue) calculated using Campbell and Bozorgnia (2006).

The modelled data are close to the observed vertical component PGA, but the horizontal observations were larger by a factor of up to ten compared to the modelled data. This difference could be due to site amplification which is not accounted for in the modelling. We also know that near surface attenuation is quite variable, which is also not accounted for. The stress drop is critical to the correct modelling of PGA and accounts for the relative differences between the two earthquakes and it is the high stress drop of the Market Rasen earthquake that results in relatively high PGA values.

Given these results, we computed PGA for a hypothetical 6.0 M_W earthquake with stress drop values of 20 bar and 200 bar, roughly corresponding to the Folkestone and Market Rasen earthquakes (Figure 3). The purpose of this computation is to show how the difference in stress drop translates into PGA, and also to get a rough estimate of ground motion for an earthquake that had a high stress drop such as the Market Rasen earthquake. Our results show that the PGA for the higher stress drop is about ten times higher. At 10 km distance the computed PGA for 6.0 M_W and the higher stress drop is of the order of 10 m/s^2 at 10 km and about 1 m/s^2 at 50 km.

One may argue how realistic these values are. The Market Rasen earthquake had an unusual high stress drop and such events seem to be rare. Preliminary results from the UK suggest that stress drop may increase with depth but not with magnitude. As the hypocentral distance is at least as large as the depth, the near-source PGA values at less than about 15 km would not be observed. If it was more likely that the larger events in the UK had a higher stress drop, the high stress drop modelling has to be considered.

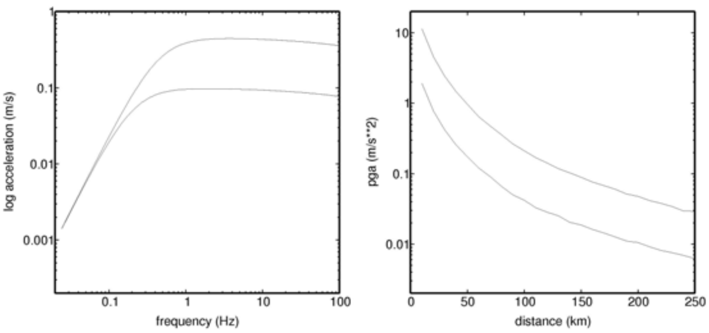


Figure 3. Simulated acceleration spectra (left) and PGA (right) for a 6.0 M_W. for stress drops of 20 bar and 200 bar. The higher value curves are for the 200 bar case.

As seen from Figure 2, the Campbell and Bozorgnia (2006) relationship underestimates PGA for the Market Rasen earthquake. However, the observations are within three standard deviations of the median PGA. The occurrence of a high stress drop event probably means that stress drop should be considered within seismic hazard estimates. This is effectively the case for the recent seismic hazard study for the UK (Musson and Sargeant, 2007) since three standard deviations above the mean are used for the ground motion relationship.

Cumulative absolute velocity – a new development for seismic hazard

In 1994, an earthquake of 4.1 ML hit the small town of Eugowra, NSW, Australia. What was remarkable about this minor earthquake was that the epicentre was close to an accelerometer installed in the town's hotel. The instrument recorded a peak ground acceleration (PGA) of almost 1g; the only damage was a few broken windows. High PGA does not mean a damaging ground motion, especially not when, as at Eugowra, the high value is in a single spike in the record at 50 Hz (Gibson et al 1995).

Traditionally, seismologists have tried to filter out such non-damaging accelerations from seismic hazard calculations by applying a cut-off at low magnitudes. All earthquakes less than some threshold value, typically around 4 Mw, are deemed to be "not of engineering significance" and ignored. The problem with this approach is that it is a very blunt instrument. The choice of cut-off is essentially arbitrary, and all earthquakes less than this value, even by 0.1 of a magnitude unit are considered non-hazardous. Seismologists have long recognised that this is not an ideal approach (Bender and Campbell 1989).

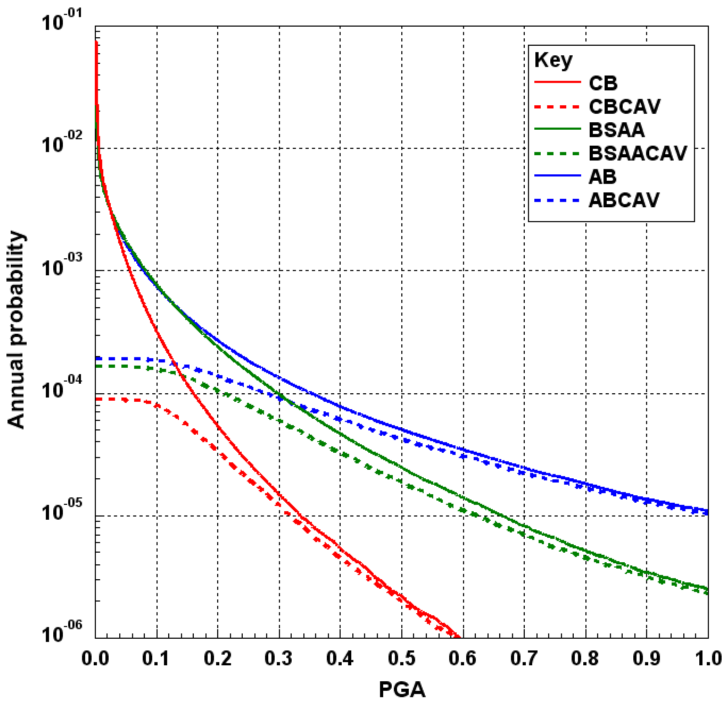
In the last few years, following a research programme conducted by the Electrical Power Research Institute (EPRI) in the USA (Kassawara and Sandell 2006), seismologists are turning their attention away from the concept of "earthquakes not of engineering significance" to "ground motions not of engineering significance", a much more logical approach. Irrespective of the originating event, a ground motion consisting of a short spike of high acceleration has no power to cause damage to well-built structures.

A property of ground motion that seems to relate closely to the capacity to cause damage is cumulative absolute velocity, or CAV. This is defined as the integral of that part of an accelerogram, when converted into absolute values, that falls within a series of one-second windows within which some part of the record exceeds 0.025g. Critically, this introduces some measure of the duration of strong shaking. Experience shows that when the CAV for a given record is less than 0.16 g-s (gravity seconds), there is never any damage to well-built structures. Thus, in the hazard calculations, one can simply discard low-CAV ground motions from consideration.

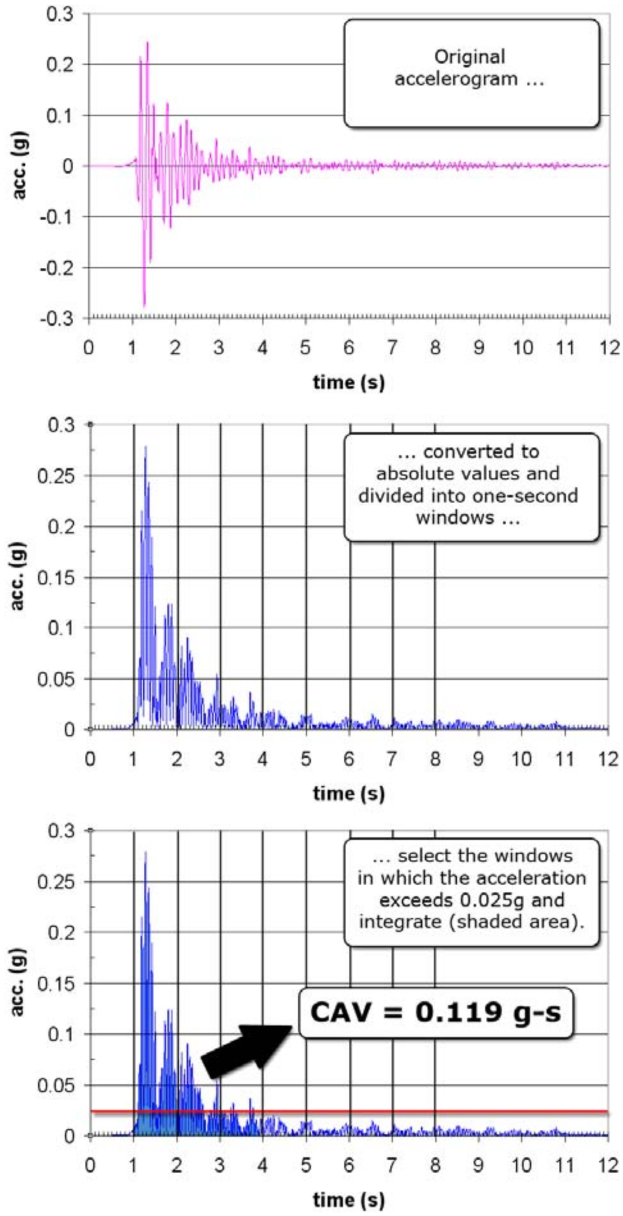
The result is a hazard curve that shows, not the probability of a given PGA, but the probability of a PGA that will also have the capacity to cause building damage. The BGS in-house hazard software was one of the first programs to be adapted to compute hazard in this way.

The effect of “CAV filtering” in an environment like the UK is striking: the reduction in computed ground motion for a given probability follows a hyperbolic function of the expected PGA without CAV filtering. For PGA around 1g, the reduction is near zero, but at and below a value that varies from case to case but is usually between 0.15-0.25 g, the reduction is 100%. The hazard curves become flat and intersect with the Y-axis at a probability between 10^{-3} and 10^{-5} depending on site. At higher probabilities than the intersection point (e.g. the 475 year return period), the hazard is effectively zero.

Some people find it hard to cope with the idea of zero hazard at a probability of, say, 10^{-3}, but in fact it is commonsense. It just means that the probability of any structurally damaging earthquake ground motion at a given site is less than 10^{-3}. Given the almost complete absence of earthquake damage to engineered structures in Britain, perhaps this shouldn’t be too surprising.



Hazard curves for St Fillans, Perthshire, using three different ground motion models, showing the results without CAV filtering (solid lines) and with (dashed lines). CB = Campbell and Bozorgnia (2008); BSAA = Bommer et al (2007); AB = Atkinson and Boore (2006).



The stages in computing CAV. This record shows the case of a small event (3.9 ML) with a relatively high PGA (almost 0.3 g). The CAV is below the threshold of damage.

Scientific Objectives

Locating historical earthquakes from macroseismic data

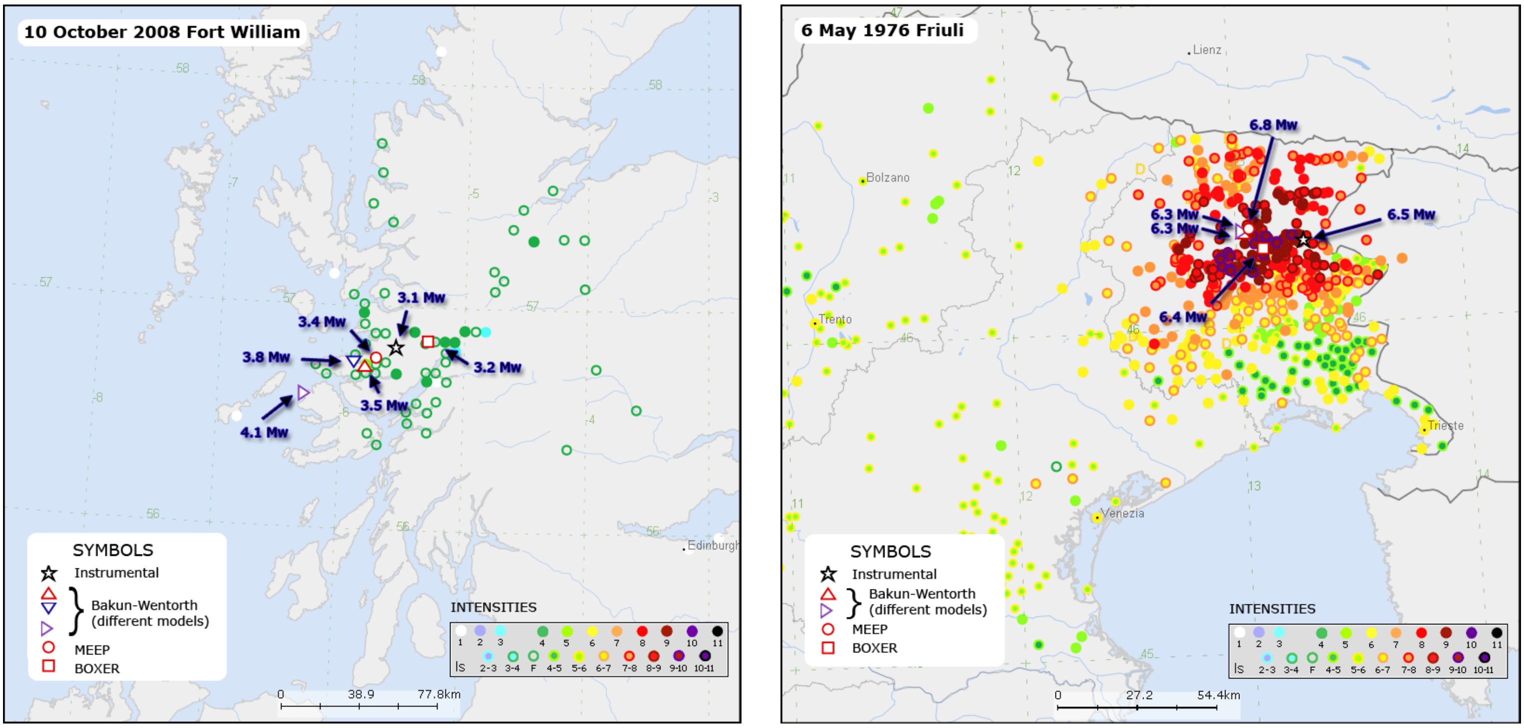
The epicentres given for historical British earthquakes in the BGS database were all derived from expert judgement; the perceived problem with this is that the decisions made lack transparency and are not reproducible. As part of the international project NERIES (http://www.neries-eu.org/), the problem of objective assessment of the parameters of pre-instrumental earthquakes was examined by BGS, with the collaboration of the Institute of Earth Sciences, Barcelona (CISC) and support from the Institute for Geophysics and Volcanology in Italy (INGV).

The two main approaches to this problem are the BOXER approach (Gasperini et al. 1999) and the Bakun-Wentworth method (Bakun and Wentworth 1997). BOXER treats the trimmed mean of the latitude and longitudes of the highest intensities as the epicentre, which leads to problems with offshore events. The Bakun-Wentworth method relies on the application of a regional model for intensity as a function of magnitude and distance, which has to be determined in advance.

For NERIES, a new approach was developed, which assesses earthquake parameters in two stages. The epicentre is determined first, by minimising the misfit of a Kövesligethy-type intensity attenuation model over a grid-search routine of trial epicentres, following a proposal of Peruzza (1992). This also estimates the focal depth. Given the epicentre, the magnitude is determined using a method based on a relation given by Frankel (1994) between magnitude and the radius of perceptibility, based on crustal attenuation Q and shear-wave velocity at 3 Hz (believed to be the frequency most perceptible to humans). From the estimated limit of the felt area for any test magnitude value, higher isoseismals can be interpolated and compared to the actual distribution of intensities, to find the optimal value.

This approach was coded as a new software tool called MEEP (macroseismic estimation of earthquake parameters). While the goal was a tool that could be applied to any data set using only easily-sourced information (e.g. regional Q) this proved not to be practicable for magnitude estimation. The Frankel formula requires an additional calibration constant, and the isoseismal spacing is not always consistent. To solve this, a calibration tool was developed that can be run on a training set of earthquakes to obtain optimal values of the regional constants required by the program.

Extensive tests by project partners on earthquakes in Italy, Greece, Switzerland, the Iberian peninsula and the UK, showed that of the three methods, none consistently out-performed the others when compared to instrumental determinations. Typically, BOXER, Bakun-Wentworth and MEEP give results that agree well for events with good sets of intensity data points, but where the intensity field is distorted because of poor reporting or topography, or irregular energy release, the three methods can be “thrown” in different ways to give inaccurate results.The most recent version of MEEP actually includes all three methods for comparison – which can give an idea of the uncertainty in the parameters.



Two contrasting examples that show all three methods for calculating earthquake locations from macroseismic data: a recent minor British earthquake (Fort William, 2008) and a large Italian one (Friuli, 1976). (Base maps courtesy of INGV)

Scientific Objectives

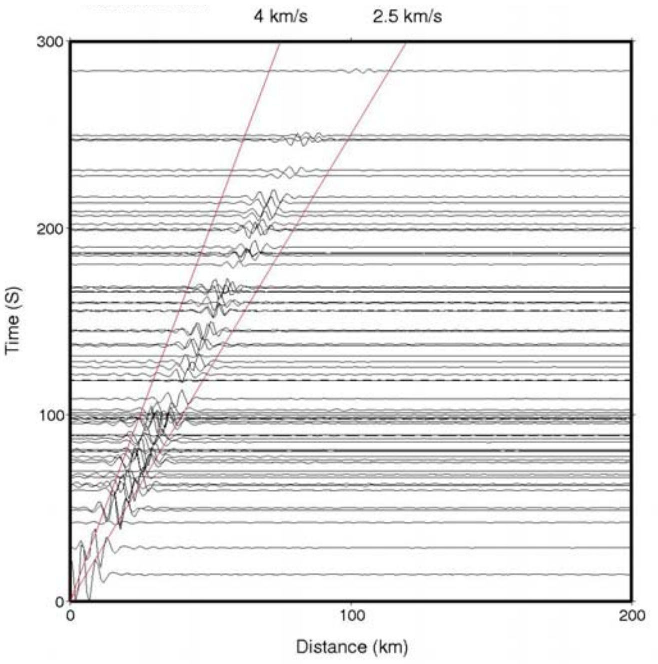
Noise Correlation

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 to broadband seismic data recorded in the UK to determine Green's Functions for surface waves at periods between 5 and 50 seconds.

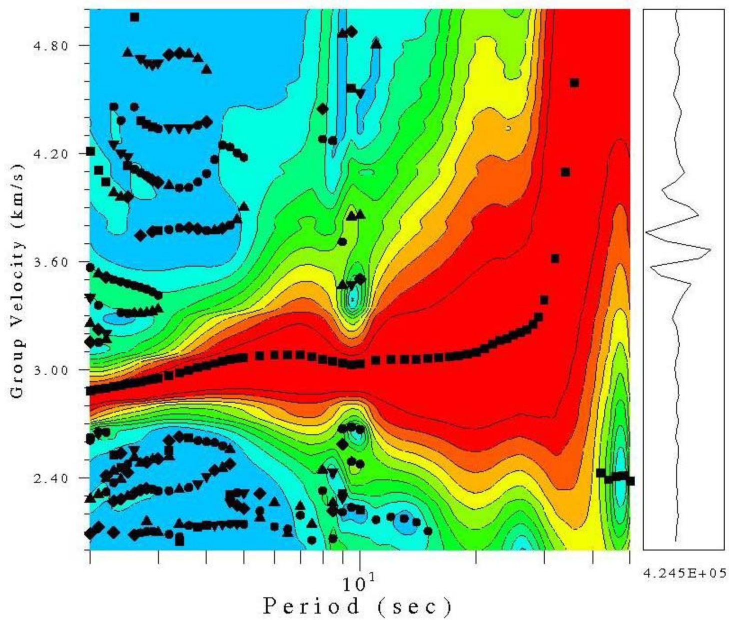
Conventional 3D seismological models of the Earth are generally obtained from recordings of waves that have travelled to a given receiver from a single, known, energy source, for example an earthquake. However, seismic waves propagate inside the Earth all the time, created by sources such as wind, ocean 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). This approach can be particularly useful in areas such as the UK where there are relatively few "active" sources.

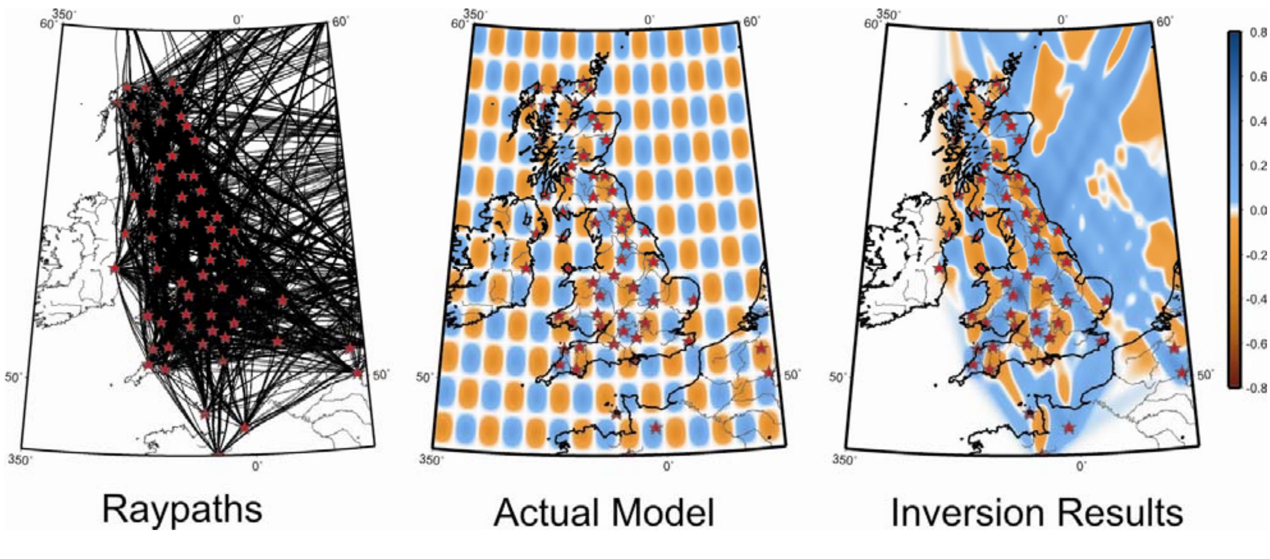
We have used data from the BGS broadband stations across the UK, along with broadband stations operated by other partner agencies across Europe to construct surface wave Green's Functions from the continuous data recorded at pairs of stations. Twenty-four hour segments of continuous data were firstly decimated, high-pass filtered, and then a one-bit normalisation was used to reduce the effect of amplitude variations in the ambient wavefield. The corresponding data segments at different stations were then cross-correlated. Cross-correlations for each stations pair were then stacked over a periods of time ranging from months to years. The resulting stacks show stable waveforms whose character is consistent with Rayleigh waves propagating between the two stations.



Surface wave Green's functions calculated by cross-correlation of ambient noise recorded at selected pairs of stations across Scotland. The Green's functions are sorted by distance, which shows that the signals are consistent with expected surface wave group speeds (shown by red lines). Also, the waveforms are very consistent along different paths.



Surface waves at different periods are sensitive to velocity structure at different depths. This can be used to construct group speed maps that show the 2-D variation of velocity in the Earth's Crust



Synthetic checkerboard tests can be used to estimate the resolution of the available data. This test uses currently available broadband stations in northwest Europe as well as a number of BGS short period seismograph stations. The checkerboard has a background velocity of 3km/s perturbed by +/-0.3 km/s. There are 81 grid points in the NS direction and 101 in the EW direction. The number of stations is 73.

Scientific Objectives

Lg-wave Attenuation

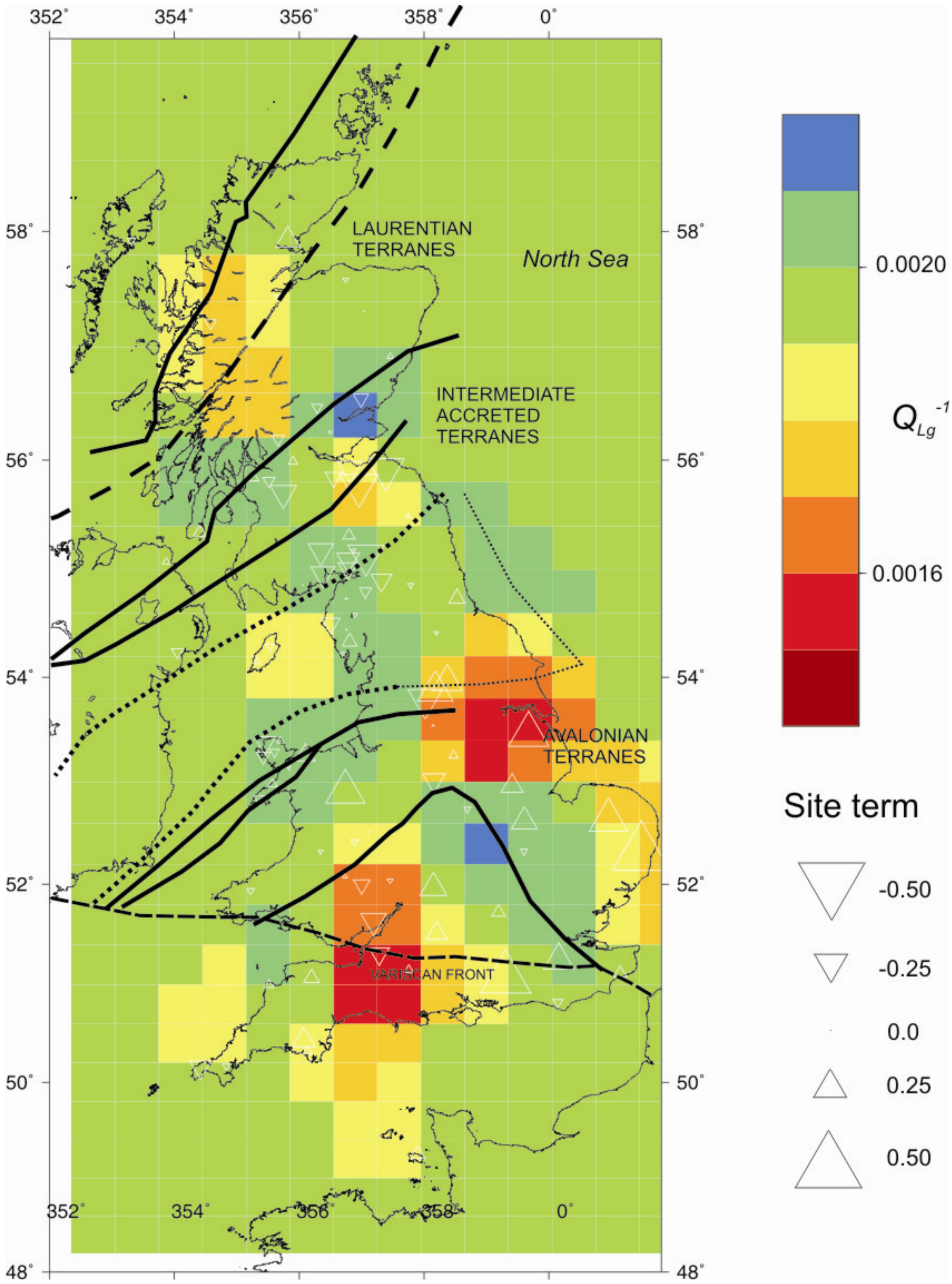
A paper to be published in Geophysical Journal International represents the culmination of a detailed investigation of seismic wave attenuation in the UK. A regional average attenuation model shows that the strength of attenuation in the UK is similar to that observed in France. Spatial variations in attenuation within the British Isles are indicated by the results of the 2D modelling. These results are vital for understanding seismic wave propagation in the UK and estimating ground motion for future earthquakes.

Lg waves (multiply reflected shear waves) are routinely used to study the crustal quality factor, Q_{Lg}, which is a direct measure of attenuation. From these measurements, material and physical properties of the Earth's interior can be inferred (Aki, 1980).

Our study area encloses much of Britain and the Irish Sea. Our aim was to investigate whether attenuation correlates with the configuration of crustal blocks (terranes) that make up the UK. To do this, we used 631 recordings of *Lg* from 64 earthquakes (2.7-4.7 M_L) and derived Q_{Lg} from the distance decay of spectral displacement amplitudes. We first determined a regional model of Q_{Lg} and in order to study lateral variations in Q_{Lg}, we divided the study area into a grid.

The spectral amplitude data contain information about the source, attenuation (the path effect) and the effects of the near-surface geology at the station (the site effect). It is well known that there are trade-offs between the effects of the source, path and the site, so verifying the results has been an important part of our investigation. Analysis of the H/V spectral ratios at the three-component stations in the UK network provides an independent check on the site terms determined from the inversion and show our results to be reliable. The trade-off between Q_{Lg} and the source term can be serious but our tests show that the effect is not severe.

Our results show that attenuation varies spatially, with regions of lower than average attenuation (high Q_{Lg}) in north-western Scotland, eastern central England, and south-western England. South-eastern England, the East Irish Sea Basin region and an area of eastern Scotland between the Southern Uplands Fault and the Highland Boundary Fault are characterised by higher than average attenuation (low Q_{Lg}). Lateral variations in Q_{Lg} do not correlate with the configuration of terranes and the cause of the variations we observe remains to be determined.


352°
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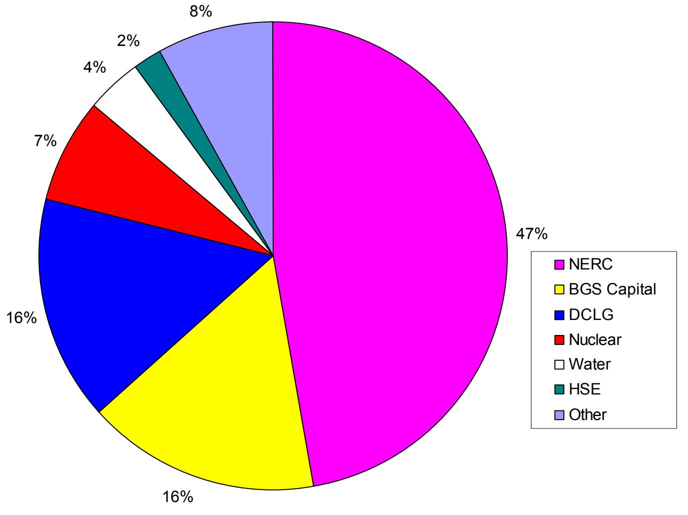
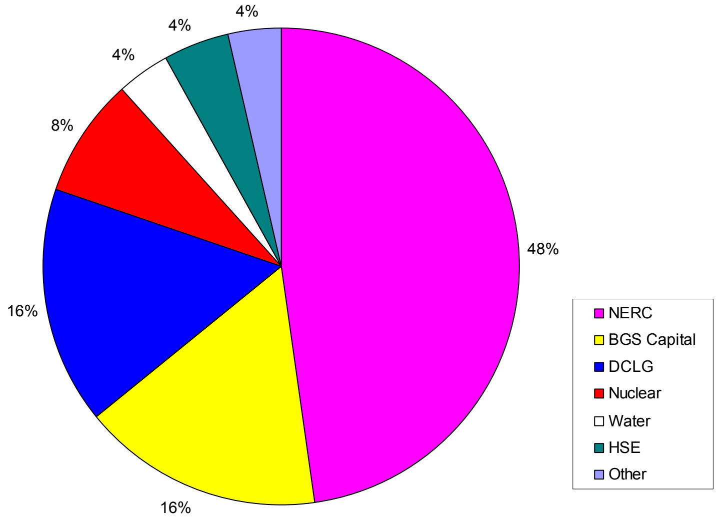
356°
358°
0°
58°
56°
54°
52°
50°
48°
LAURENTIAN TERRANES
North Sea
INTERMEDIATE ACCRETED TERRANES
AVALONIAN TERRANES
VARISCAN FRONT
0.0020
0.0016
Q_{Lg}^{-1}
Site term
-0.50
-0.25
0.0
0.25
0.50

Funding and Expenditure

In 2008-2009 the project received a total of £595k from NERC. This was matched by a total contribution of £463k from the customer group drawn from industry, regulatory bodies and central and local government. In addition, we received a further £200 k in BGS capital funds as part of a five year spending plan to upgraded the seismic monitoring network and improve data quality of science. This money was spent on the purchase of new instrumentation and improvements in station and network infrastructure.





The projected income for 2009-2010 remains approximately the same. There has been a slight decrease in the level of funding from NERC to £585 k. We have now signed agreements with a number of customers in the nuclear industry for continued support of the project up to 2011. This runs in parallel to the long-term support from the Department for Communities and Local Government, DCLG.

Acknowledgements

This work would not be possible without the continued support of the Customer Group. 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 Project Team

BGS Seismic Monitoring and Information Service

Brian Baptie	Project Leader

Research

Roger Musson	Seismic Hazard
Lars Ottemoller	UK & Regional Seismicity
Alice Walker	UK & Regional Seismicity
Susanne Sargeant	Seismic Hazard
David Booth	Crustal Structure
Richard Luckett	Seismic Data Processing

Outreach

Aoife O'Mongain	Media and Communications

Analysis Team

Glenn Ford	Seismic Analyst
Davie Galloway	Seismic Analyst
Bennett Simpson	Seismic Analyst
Julian Bukits	Seismic Analyst

Technical Operations

John Laughlin	Senior Electronics
Andy Blythe	Field Engineer
Heiko Buxel	Field Engineer
Tony Swan	Field Engineer

Computing Support

Dave Scott	Software Engineer

Consultant

David Kerridge	Theme Leader

Appendix 2 Publications

BGS Internal Reports

Baptie, B. 2008. Earthquake Monitoring 2007/2008, BGS Seismic Monitoring and Information Service, nineteenth Annual Report, BGS Internal Report IR/06/??.

Galloway, D. A., 2007. Bulletin of British earthquakes 2007, BGS Report CR/06/???.

Luckett, R., B. Baptie and L. Ottemöller. Automatic moment tensor determination as part of a tsunami warning system. British Geological Survey, Commissioned Report CR/08/143, 2008.

Musson, R.M.W. and Winter, P.W., 2008. Objective assessment of source models for seismic hazard studies, British Geological Survey Open Report, OR/08/053.

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Ottemöller L., R. Luckett and B. Baptie. Tsunami earthquakes and slides. British Geological Survey, Commissioned Report CR/08/142, 2008.

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

External Publications

Baptie, B. and M. Corbin, 2008. Changes in seismic velocity resulting from lava dome collapse measured using passive seismic interferometry, Proceedings of the IAVCEI General Assembly, Rekjavik, Iceland.

Baptie, B., 2008. Seismotectonics and state of stress in the British Isles, Proceedings of the World Stress Map Conference, Potsdam, Germany.

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Appendix 3 Publication Summaries

Seismotectonics and state of stress in the British Isles

B. Baptie

Both the underlying causes and the spatial distribution of earthquake activity in the British Isles remain poorly understood. In this study, I present focal mechanisms determined for twenty-eight British earthquakes of magnitude $M_L > 3.0$ that can be used to examine the nature and coupling of some of the competing ideas on crustal stress and the driving forces for earthquake activity in the British Isles. The resulting focal mechanisms are mainly strike-slip with northwest-southeast compression and northeast-southwest tension, or reverse, with northwest-southeast compression. This results in dips for the P axes that are sub-horizontal, while the T axes vary from horizontal to vertical. The P-axes orientations for most events cluster between north and northwest. The orientations of the principle stresses found by inversion of the focal mechanims data are a sub-horizontal σ_1 striking northwest-southeast, a near vertical σ_2, and σ_3 striking southwest-northeast. The relative magnitude of the principal stresses is given by the parameter, $R=(\sigma_3 - \sigma_1)/(\sigma_2 - \sigma_1) = 0.7$, suggests that $\sigma_1 >> \sigma_2 > \sigma_3$, i.e. σ_2 and σ_3, are relatively close in value, resulting in a prolate stress ellipsoid stretched along a NW-SE axis. The observed spatial variation in P-axes orientation between north and south is different from the orientation of the maximum horizontal compressive stress, S_H, expected for northwest Europe from first order plate boundary forces. This may suggest that the northwest southeast compression expected for the region is modified by flexure dependent stresses resulting from glacio-isostatic adjustment (GIA), resulting in a change to the expected σ_1 direction in northern Britain. However, to fully understand the relative magnitude of horizontal strains from ridge push and GIA we need long term geodetic data that will allow use to compare horizontal deformation rates.

Post-Collapse Banded Tremor At The Soufriere Hills Volcano, Montserrat, West Indies.

B. Baptie

A major collapse of the Andesitic lava dome at the Soufrière Hills Volcano occurred on 29 July 2001. This resulted in the loss of approximately 45 million cubic meters of material from the lava dome over a period of 8-9 hours and the creation of a major collapse scar. The collapse was followed by an episode of banded tremor recorded on the seismograph network that continued for over 2 months with the interval between the peaks in the tremor activity varying between 6-30 hours. The duration of the tremor bands is typically 1-3 hours. The tremor bands appear to be composed of small long-period earthquakes that merge together to form tremor, although rockfall activity also increases during these tremor episodes, and are sometimes accompanied by venting of ash. The dominant period of the tremor bands can remain approximately constant or change slowly over an interval of several days. Though at other times the tremor can stop for an interval of a few days before restarting again. We suggest that the occurrence of the tremor bands is controlled by the magma supply rate in the upper conduit and has developed as a result of the collapse, which reduced the overpressure and increased magma ascent rate, allowing gas-rich magma to rise quickly to the surface. Degassing magma at the top of the conduit, results in an increase in pressure below the lava dome and the occurrence of the tremor bands and in the extrusion of fresh material, as indicated by the increase in rockfall activity and gas venting. If this is the case the duration of individual tremor bands should be related to the degassing and extrusion processes.

Changes in seismic velocity resulting from lava dome collapse measured using passive seismic interferometry

B. Baptie and M. Corbin

The collapse of the lava dome of the Soufriere Hills Volcano on Montserrat in July 2003 is the largest recorded in historical times, with over 200 million m3 of material removed in less than 24 hours. Here, we use passive seismic interferometry to measure the changes in seismic velocity that resulted from this collapse. Following recent research that has shown that the cross-correlation of continuous seismic data at two stations provides an estimate of the impulse response between the two stations, we retrieve the Green’s functions from ambient noise along paths that intersect the volcanic edifice for a period of three months before and after the dome collapse on 12-13 July 2003. We then use a Coda Wave Interfometry (CWI) approach to measure small changes in the delay time, $\delta\tau$, at different lapse times, τ, by comparing each Green's functions with a reference Green's function obtain by stacking. The ratio $\delta\tau/\tau$ can then be used as a proxy for relative velocity change, $\delta v/v$. The Green's functions in the three-month period prior to the collapse are found to be extremely stable with only very small changes in relative velocity. However, following the collapse we see much larger changes that are interpreted in terms of the unloading of the lava dome. In addition, the lava dome collapse was preceded by a swarm of approximately 9000 earthquakes with very similar waveforms, suggesting a highly repeatable source. We also apply CWI to these data to examine changes over a smaller time scale but with higher resolution. Individual events are again compared to a reference event obtained by stacking. Although there are systematic changes in the delay times at different lags at individual stations, these changes vary from station to station making it difficult to interpret these results in terms of a change in seismic velocity of the volcanic edifice. Instead, the small changes in event properties probably show that the properties of the seismic source are changing in the period leading up to the collapse, possibly indicating increasing pressurization.

UK 1-D regional velocity models by analysis of variance of P-wave travel times from local earthquakes

D.C. Booth

A method is presented for deriving 1-D velocity depth models from earthquake bulletin data. The models can be used as initial models for more advanced modelling techniques such as tomographic inversion. The method is useful when there is little or no refraction and long-range reflection survey data. The bulletin travel times are subjected to an analysis of variance, where they are separated into source, distance, and receiving station terms. The distance terms describe the variation of travel time with distance, and the associated trend lines allow 1-D velocity models for the crustal layers to be determined. The velocity models provide an average crustal model for the region derived from local data. This does not include superficial layers which are necessarily poorly determined. Earthquake bulletin P-wave data from propagation paths across three different regions of the UK are employed to illustrate the use of the technique.

Chicken or Egg? Turning Earthquakes Into Virtual Seismometers

A. Curtis, H. Nicolson, D. Halliday, J. Trampert and B. Baptie

The global array of permanent seismometers that record seismic energy is confined almost exclusively to accessible and secure, land-based sites, while the spatial distribution of global earthquakes is highly heterogeneous and is often most dense beneath the ocean margins. This limits the resolution of subsurface images, and results in relatively few local measurements from areas of great geological and tectonic interest (mid-ocean ridges, the Tibetan and Andean plateaus, subduction zones). While standard seismic interferometry allows the Earth to be imaged using ambient seismic energy recorded at seismometers, the current and planned future global seismometer distribution will remain a serious cause of bias in our knowledge of the subsurface. Here we show that a different form of interferometry can be used to construct an artificial or 'virtual' sensor from any well-recorded energy source. We demonstrate this by turning two earthquakes in south-west USA into virtual seismometers located beneath the Earth's surface. Such sensors inherit the spatio-temporal response function from the radiation pattern of the original energy source; since earthquakes impart strain, the virtual seismometers are strain sensors. By definition earthquakes are located within the Earth's solid interior, so virtual seismometers can be located non-invasively inside solid bodies. Earthquakes occur precisely within many tectonically active areas of most interest in which there are often no real seismometers; their corresponding virtual seismometers provide local windows into such geological phenomena.

The Acquisition of Source, Path, and Site Effects from Microearthquake Recordings Using Q Tomography: Application to the United Kingdom

B. Edwards A. Rietbrock , J.J. Bommer and B. Baptie

Source, site, and propagation parameters are inverted from a U.K. database of weak-motion events (2.0>ML>4.7). This results in the complete spectral parameterization of over 3200 velocimetric records of 273 events from the year 1992 to 2006. The S wave is extracted from the vertical records and is processed using a multitaper Fourier transform. We initially use a nonlinear least-squares log-space optimization to obtain estimates of the attenuation parameter for each spectrum. The estimates of t* are then used to geometrically constrain a depth-dependent Q model using a technique adapted from velocity tomography. We then invert for the remaining frequency-dependent parameters and a collective amplitude parameter from the velocity spectra while fixing the newly computed attenuation parameters based on raytracing through our Q model. The resultant amplitude parameters are then split into source moments, apparent geometrical spreading, and site correction factors. We find a frequency-independent depth-dependent Q structure. A linear relationship proportional to 0.7 ML between moment magnitude (Mw) and local magnitude (ML) is found in the range of 2–4.7 ML. The majority of stress drops are found to range on the order of 0.1–10 MPa. A multiple segment apparent geometrical spreading model is found to best describe the amplitude decay with distance, accounting for factors such as geometrical spreading and scattering, along with multiple phase interference in the analysis window. Site response functions are found to broadly correlate with regional geology, mean amplification occurring in the Cenozoic sedimentary rock sites to the southeast of England relative to the harder Palaeozoic rock sites of Wales and Scotland. We use a bootstrap analysis technique to analyze the dependence of our results on the data in order to estimate the variance of the results and check the robustness of different inversions. Synthetic spectra are also computed in order to obtain minimum variance and bias of model parameters associated with the method. In applying a geometrical Q constraint, through the use of Q tomography, we find that the robustness of the results is significantly increased. A thorough analysis of the trade-offs involved in the inversion is performed using synthetic datasets. We find strong trade-offs between the parameters, but we are able to show that this covariance is reduced when adopting the Q-tomography approach.

Impact of a Lisbon-type tsunami on the UK coastline, and the implications for tsunami propagation over broad continental shelves

K.J. Horsburgh, C. Wilson, B.J. Baptie, A. Cooper, D. Cresswell, R.M.W. Musson, L. Ottemoller, S. Richardson, S.L. Sargeant

We investigate the propagation of tsunamis towards the European shelf break, using six different initial conditions (based on the 1755 Lisbon earthquake), in order to assess the hazard to this region. Only one of our source models, an assumed earthquake magnitude of 8.7 Mw with a zonal fault orientation, resulted in significant wave heights at the UK coastline. Due to wave spreading only a fraction of the tsunami energy from such an event reaches the northwest European shelf, which itself provides a further buffer through reflection and frictional dissipation. However, we found significant local re-amplification due to wave interactions and resonance on the continental shelf. The maximum elevations obtained were comparable to severe winter storm conditions, but with extreme local variability in the tsunami amplitude. Our results suggest that the impact of any repeat of this event would be very sensitive to the precise location and orientation of the source deformation, as well as by complex topographic interactions on the shelf. The uncertainties arising from the combination of source orientation and bathymetric interaction suggest that any assessment of risk, for places where tsunamis are likely, should consider a large ensemble of initial conditions.

A Tsunami Warning System for the Northeast Atlantic

R. Luckett, L. Ottemoller and P. Whitmore

In 2006, the UK Department for Food and Rural affairs (DEFRA) commissioned the British Geological Survey (BGS) to establish a system capable of detecting and discriminating earthquakes which could pose a tsunami risk to the UK. Previous studies for DEFRA had shown that the UK risk from tsunamis is low, but not negligible. The system must be able to become part of an integrated tsunami warning process, if one is implemented in the future. Rather than start from scratch in developing suitable earthquake detection software, the BGS chose to implement the EarlyBird software developed at the US NOAA West Coast and Alaska Tsunami Warning Center (Whitmore and Sokolowski, 2002). By selecting stations from seismic networks in over a dozen countries a composite network of more than 100 stations was built up that provides good coverage for our area of interest, which extends from the UK and surrounding waters to most of the North Atlantic, including offshore Portugal, the Mid-Atlantic ridge, the Caribbean, and the northeast coast of America. The system has now been operating reliably for over a year and has detected earthquakes in most of the areas identified where potentially tsunamigenic sources could affect the UK. The detection threshold has been shown to be well below that required, considering that significant tsunamis are likely to be generated only by earthquakes of magnitude over 6.5, and response times for alert messages are good. If a tsunami warning centre is set up within the UK we are confident that the system described here would fulfil the seismic requirements. In addition such a centre would need access to real-time deep sea pressure sensors, tide gauge instruments (these aspects are under investigation by the Proudman Oceanographic Laboratory) and tsunami forecast tools as well as reliable means to disseminate warnings.

Volcanic seismicity at Montserrat, a comparison between the 2005 dome growth episode and earlier dome growth.

R. Luckett, S. Loughlin, S. De Angelis and G. Ryan

In 2005 Soufrière Hills Volcano on Montserrat started its third major episode of dome growth since the current eruption started in 1995. The style of seismicity associated with dome growth has changed, in particular the events known as ‘hybrid’ earthquakes have reduced in numbers by an order of magnitude compared to previous dome growth episodes. In the past, hybrid earthquakes have been associated with magma ascent and so it is surprising to observe prolonged periods of rapid dome growth during which very few hybrid earthquakes are recorded. In addition, the frequency of the codas of hybrid earthquakes, as well as of some of the so called ‘long-period’ events, has changed. The changes in recorded seismicity have had a marked effect on the techniques used to monitor the state of the volcano and those events that continue to be recorded in large numbers (‘rockfall events’) have been used to assess the state of activity at the volcano.

Automatic moment tensor determination as part of a tsunami warning system

R. Luckett, B. Baptie and L. Ottemöller

Knowledge of the faulting mechanism of earthquakes is relevant to tsunami warning as it constrains vertical seafloor displacement and thus, potentially, tsunami height. The seismic moment tensor is a commonly used mathematical representation of the earthquake source that can be calculated from recordings of earthquakes and uniquely describes fault geometry. The objective of this work was to implement software to compute the seismic moment tensor for earthquakes in real-time as part of a tsunami warning system, and to evaluate its performance and limitations. The EarlyBird software implemented in the previous phase of the project has a module which calculates the moment tensor, however, the results from it are not routinely used in decision making by those warning centres currently using the software. We added the moment tensor inversion module to our existing EarlyBird system so that we could test it in real-time over a period of many months. In addition to the real-time testing, we tested the moment tensor module in simulated real-time and compared the results to accepted solutions determined by a global agency. While the system generally worked well, there are earthquakes for which the EarlyBird moment tensor is quite different from those calculated by established global agencies. To see if this could be improved, we investigated the dependency on data and processing parameters. We found no systematic problem, but that there are earthquakes for which the moment tensor cannot be reliably determined automatically. In these cases, intervention from a knowledgeable seismologist is required to evaluate the solution and perhaps to change source depth and remove bad stations. This is also true for other parameters like the hypocentre location and magnitude, as described in the previous report. The moment tensor solution becomes available about 20 minutes after the event. In the context of tsunamis that might affect the UK, it is unlikely that the moment tensor would influence a decision to issue a warning. It could, however, provide important additional information useful when modelling tsunamis and estimating wave heights.

Objective assessment of source models for seismic hazard studies

R.M.W. Musson and P.W. Winter

Up to now, the search for increased reliability in probabilistic seismic hazard analysis (PSHA) has concentrated on ways of assessing expert opinion and subjective judgement. Although in some areas of PSHA subjective opinion is unavoidable, there is an all too present danger that assessment procedures and review methods simply pile up further subjective judgements on top of those already elicited. Such reviews are in danger of assessing only the form and neglecting the content. The time has come to find ways to demonstrate objectively, where possible, if interpretations are valid or not. This can be done by studying what these interpretations physically mean in terms of seismicity. Experience shows that well-meaning but flawed design decisions can lead to source models that are actually incompatible with seismic history. One such method is as follows: from a seismic source model one can generate large numbers of synthetic earthquake catalogues that match the completeness thresholds of the historical catalogue. The question is then posed, is the historical earthquake catalogue a credible member of the set of all possible catalogues derived from the model? If the answer to this is no, and this can be determined statistically, then one can reject, with a specified confidence level, the hypothesis that the model is a valid depiction of the long-term seismicity rates that will govern the future hazard.

The seismicity of the British Isles to 1600

R.M.W. Musson

This report is the product of a study by the British Geological Survey (BGS), partly in support of work package NA4 of the NERIES project. A large amount of research was done during the 1980s by BGS and others on the historical seismicity of the UK. This was used as the basis of a catalogue of British earthquakes published in 1994, which acted as a synopsis of all previous research (Musson 1994). However, this catalogue concentrates chiefly on the period after 1700. Events prior to this date are treated in a fairly cursory fashion.

This report looks at an earlier period by examining all known earthquakes in the British Isles up to the year 1600 and presenting discussion of each, drawing on a mixture of previous studies and original material. Tables of places and intensities are presented where possible; however, the practice is not followed of assuming that an entry in the annals of a monastery means that the earthquake was necessarily felt in that monastery, unless it is specifically stated. Thus, for many events that are noted without any details in original sources, one can reliably deduce very little.

Some events that have been previously accepted by previous catalogues, e.g. Davison (1924) are concluded to be dubious or fake, and these are generally included even in cases where it was established some time ago (e.g. in Ambraseys and Melville 1983) that these events were wrong (usually misdatings of other earthquakes). It is difficult to maintain a completely consistent approach to including comments on fake events – to try and include every mention that has ever been made of any earthquake would lead to the unhelpful inclusion of many obscure references.

The Macroseismic Survey of the 27 February 2008 Market Rasen Earthquake

R.M.W. Musson

Immediately following the occurrence of the Market Rasen earthquake on 27 February 2008 (5.2 ML, 4.5 Mw), an online questionnaire was opened on the BGS web site to collect felt reports. In addition, questionnaire data were collected automatically by USGS as part of the “Did You Feel It?” (DYFI) programme (Wald et al. 1999), and also by EMSC as part of its European monitoring. Some additional data was also gathered by agencies on the fringe of the felt area, notably ROB in Brussels, and DIAS in Dublin. No data were received by BCSF in France. This report summarises the findings of the survey.

The case for large (M > 7) earthquakes felt in the UK in historical times

R.M.W. Musson

Evidence from seismic and bathymetric surveys along the passive margin of NW Europe indicates that there are a number of features suggestive of large earthquakes having occurred in geologically recent times, although the exact timing of these events is difficult to establish. It might be thought that, although such large earthquakes may have occurred, for example, in immediate post-glacial times in response to rapid isostatic readjustment, no earthquake in the UK area in historical times has exceeded a value of around 5.7 Mw. However, in past interpretations of regional seismicity, the possibility that some known historical earthquakes were in fact passive margin events has not really been canvassed. A large, distant, offshore earthquake is likely to be felt only at moderate strength over well-populated areas without any observable damage concentration. In a period when documentation of earthquakes is always sparse, such an occurrence is likely to lead to vague reporting that will not be easily interpretable. Looking at the historical record with this in mind, it is possible to identify some earthquakes that are at least compatible with an offshore interpretation, as shown in a series of case studies. However, in no case is such an interpretation the only one viable. Also, some cases that initially appear to be potentially passive margin events can in fact be discounted. While there is no unequivocal evidence for large earthquakes having occurred on the NW European passive margin in historical times, neither can the possibility be rejected, and examination of the record shows one event in particular (in 1508) which may be a large passive margin event. Thus the regional maximum magnitude could possibly be larger than has hitherto been assumed.

Some notes on regional variations in intensity attenuation

R.M.W. Musson

Compared to models for the prediction of physical measures of earthquake strong ground motion, macroseismic intensity has received relatively little attention. Classic studies of the subject have been couched in terms of studies of the decay of intensity (I) with distance from the epicentral intensity (Io), leading to the concept of “attenuation studies”. Recently, the term “attenuation” has become unfashion-able in engineering seismology because what is desired is to estimate the absolute value of ground mo-tion at distance R from an event of magnitude M; not the attenuated value from some central value. Comparable models, predicting expected intensity for different magnitudes and distances, are relatively uncommon; nevertheless, they can be very useful for estimating expected effects from some future earthquake; or rapid estimates of effects of an earthquake that has just occurred; or for general studies of earthquake hazard and risk.

In the 1990s a survey of European practice was made by the ESC Working Group Macroseismology, which highlighted that many countries were still relying on models of the form Io – I = fn [R] rather than I = fn [M, R]. The author at that time attempted to compile a collection of models of the form I = fn [M, R] for different parts of the world, a work which included constructing such models for some countries from available datasets of isoseismals. Today, far more macroseismic data are available online as IDP (intensity datapoint) sets, though constructing intensity models from IDPs has some pitfalls, as shown by Baumont and Scotti (2006). The author’s collection of regional relationships based on isoseismal data reveals some interesting comparisons – the models for New Zealand and Turkey, for instance, are prac-tically identical. Plotted together, the models fall strongly into two groups corresponding to intraplate and interplate areas, where, very approximately, the predicted values for an intraplate event are around two degrees higher than a corresponding interplate event.

Combining macroseismic data from multiple online sources: Example of the 27 February 2008 Market Rasen (UK) Earthquake

R.M.W. Musson, D.J. Wald, V. Quitoriano, S. Gilles, T. Camelbeeck and T. Blake

The earthquake of 27 February 2008, with epicentre near Market Rasen, in eastern England, provided a rich macroseismic data set and an interesting opportunity to investigate comparative macroseismic data collection. Previous international co-operation in macroseismology has tended to be in the form of the exchange of intensity data points (IDPs) with values assigned by respective national agencies, in cases of cross-border earthquakes (e.g. 1992 Roermond). With the popularity today of online macroseismic surveys, the assignment or reassignment of intensity values according to different procedures becomes relatively easy. Thus the possibility exists to share raw questionnaire data, assigning intensity in a uni-form way to the entire data set, a great improvement on combining IDPs that may be inconsistent at national borders. In the case of the Market Rasen earthquake, BGS collected 19,927 online question-naire responses, while the USGS, through the “Did you feel it?” (DYFI) programme, collected a further 10,794, and EMSC 596. A further 31 reports were obtained from Belgium and Ireland. These data were merged and EMS-98 intensities assigned according to BGS procedures to 2,763 locations (including “felt” for places with few responses). A number of issues arose, however, with respect to merging data. Aside from the minor consideration of file formats, significant differences between the USGS and BGS questionnaires meant that some key EMS-98 diagnostics are unreported in DYFI data (e.g. people run-ning out in alarm), some are reported inconsistently (BGS records objects falling; for DYFI only objects falling from shelves are noted), and some DYFI diagnostics are not collected by BGS (e.g. people walk-ing unsteadily). This limits the degree of interchangeability of data sets, and points out the desirability of adopting a common format for macroseismic data.

Earthquake parameter estimation from historical macroseismic data for the European-Mediterranean area

R.M.W. Musson and M.-J. Jiménez

Under the frame of the NERIES module NA4 "Archive of Historical Earthquake Data", a review has been made of existing methods of deriving earthquake parameters (epicentre, depth, magnitude) from macro-seismic data. Two major types of approach can be seen in the existing literature: methods based on fitting some form of attenuation model to the data in which it is desired to minimise residuals; and meth-ods based around some property of the highest intensity values. In the first class can be found methods proposed by Peruzza and by Papazachos in the early 1990s, and that of Bakun and Wentworth. The second class is best known for the “Boxer” program of Gasperini and others, in which the epicentre is defined as the mean of the trimmed highest value intensity data points (IDPs - either purely Imax or in-cluding the next lower intensity level or levels if the number of points are few). Where the data are relatively poor, as is often the case for historical events, a surface-fitting approach is likely to be more ro-bust, and more capable of dealing with cases where the epicentre is in fact offshore or in an unpopu-lated area. To meet the specific requirements of NA4, a set of procedures is proposed, in which an initial Boxer-like approach is used to seed a grid search in which the Köveslighethy model is fitted to the data to find a best fit location, taking into account, firstly, the effect of depth, and secondly, the fact that the actual highest intensity may not be represented by any IDP in the data set. Given the epicentre and op-timised depth, expected intensity distributions given possible magnitudes are then compared to the data in a similar way to find the best fit. This provides the estimate of the magnitude. Tests of the method to date appear promising.

Aftershock activity in the UK

R.M.W. Musson, S.L. Sargeant and L. Ottemöller

It has been observed in the last 40 years that the larger British earthquakes have shown strong contrasts in aftershock behaviour. Some have had extended sequences of aftershocks, others almost none at all. Examination of historical data confirms this, and shows that some locations tend to consistently produce strong aftershock activity while others consistently do not. In this study we examine the spatial distribution of those events that have had long aftershock sequences and attempt to relate the contrast between these and less prolific sequences to tectonic distinctions and characteristics of the earthquake rupture. If a binning strategy is applied, average number of aftershocks can be related to mainshock magnitude, even though this breaks down for individual events. From this relationship it can be computed that fractal dimension of seismogenic faulting in the UK is 1.48.

Seismicity of St Helena

R.M.W. Musson and D.N. Holt

St. Helena is an island in the middle of the South Atlantic Ocean, approximately 800 km east of the mid-Atlantic ridge. The nearest continental land masses is Africa, 1930 km away. Despite its remote location and small population, it does in fact have a record of historical seismicity going back to the mid 18th century. None of the known events is reported to have caused any damage, and seem to have been (so far as can be judged) small local earthquakes associated with a volcanic seamount. We have no records of earthquakes felt on the island since 1864, and modern instrumental seismicity in the area has not been close to St Helena. The best-described event is that of 21 September 1817, which occurred during the period of Napoleon Bonaparte's exile on the island

World earthquakes

R.M.W. Musson

This article gives a general account of the study of large earthquakes, intended for a popular audience.

Seismic activity associated with a probable submarine eruption near Tristan da Cunha, July 2004-July 2006

A. O'Mongain, L. Ottemoller, B. Baptie, D. Galloway, D. Booth

In July 2004, earthquake activity felt on the South Atlantic island of Tristan da Cunha caused widespread alarm, as seismic activity had preceded a destructive volcanic eruption in 1961. Analysis of data from two seismograph stations on the island shows a dramatic increase in earthquake activity beginning on 29 July 2004, with over 2000local earthquakes detected between July and December 2004. Furthermore, we find that the initial earthquake activity shows a consistent increase in amplitude with time, culminating in four magnitude 4.7-4.8 *mb* earthquakes on 29/30 July, the largest detected over the monitoring period. There is no evidence of precursory activity in the period before 29 July 2004. We estimate the location of the earthquakes using the relative P-wave arrival times at the two stations, S-P arrivals times and azimuths determined from P-wave polarization analysis. Our analysis suggests that, despite the relatively large errors associated with sparse data, all the events are located 37-53 km SSE of the island at a relatively shallow depth and may be associated with an offshore submarine volcanic eruption. The distinctive increase in both number of events and their amplitudes with time on 29 July can be interpreted as strong evidence for volcanic activity, with magma forcing its way up through the crust. In addition, the high b-value may suggest that the stresses causing the observed seismicity are a result of volcanic rather than tectonic activity. The offshore location is consistent with independent observations of pumice found floating near

Tristan in August 2004 and washed up on some of its beaches. A submarine seamount, 26 km south of Tristan, is located close to the area where we have located the seismic activity. The July 2004swarm, and its abrupt onset, is a reminder that this volcanic complex is still active, and there is clearly a potential for further large earthquakes and swarm earthquakes associated with volcanic activity.

Seismic hybrid swarm precursory to a major lava dome collapse: 9–12 July 2003, Soufriere Hills Volcano, Montserrat

L. Ottemöller

A swarm of ≈9500 hybrid earthquakes preceded the 12–13 July 2003 dome collapse at Soufriere Hills Volcano, Montserrat. Most events had nearly identical waveforms and cross-correlation was applied to measure inter-event periods as well as phase arrival times to determine accurate relative location. Hypocenter depths were shallow (b3 km), and relative locations were confined to a radius of b150 m. This small source volume is consistent with the observed waveform similarity. Changes in inter-event periods and energy release, measured from the seismic records, showed that the volcano evolved through several energetic states, possibly linked to cyclic magma movement. Shorter inter-event periods were linked to higher energy release rates and possibly reflect increased pressurization during periods of low extrusion rates.

Seismic monitoring at the British Geological Survey

L. Ottemoller

The British Geological Survey (BGS) monitors the seismicity in and around the British Isles. The seismic network was started in the seventies and built up over the years to 146 short-period stations. An upgrade of this network started a few years ago and will result in a modern network with broadband seismometers, high dynamic range digitizers and real-time communication (Internet, ADSL, satellite). In total the network will comprise about 50 stations, with only few short-period stations remaining. Equipment is used from both Guralp and Nanometrics, and their respective software for data acquisition is used to bring the data to the centre in near real-time. The automated data processing is done through Earthworm. Event data are analysed using SEISAN. Continuous data are kept for all broadband stations and checked for quality and completeness. Real-time data is also exchanged with neighbouring networks. The data is used for routine monitoring, but also research. Our main research objectives are to understand distribution of seismicity and relating earthquakes to tectonics, develop velocity and attenuation models and study the seismic hazard and earthquake effects.

Seismo-acoustic analysis of the Buncefield oil depot explosion in the UK, 2005 December 11

L. Ottemoller and L. G. Evers

A massive vapour cloud explosion occurred at the Buncefield fuel depot near Hemel Hempstead, UK, in the morning of 2005 December 11. The explosion was the result of an overflow from one of the storage tanks with the release of over 300 tons of petrol and generating a vapour cloud that spread over an area of 80 000 m2, before being ignited. Considerable damage was caused in the vicinity of the explosion and a total of 43 people were injured. The explosion was detected by seismograph stations in the UK and the Netherlands and by infrasound arrays in the Netherlands. We analysed the seismic recordings to determine the origin time of 06:01:31.45 ±0.5 s (UTC) from P-wave arrival times. Uncertainties in determination of origin time from acoustic arrival times alone were less than 10 s. Amplitudes of P-, Lg and primary acoustic waves were measured to derive decay relationships as function of distance. From the seismic amplitudes we estimated a yield of 2–10 tons equivalent to a buried explosion. Most seismic stations recorded primary and secondary acoustic waves. We used atmospheric ray tracing to identify the various travel paths, which depend on temperature and wind speed as function of altitude, leading to directional variation. Refracted waves were observed from the troposphere, stratosphere and thermosphere with a good match between observed and calculated traveltimes. The various wave types were also identified through array processing, which provides backazimuth and slowness, of recordings from an infrasound array in the Netherlands. The amplitude of stratospheric refracted acoustic waves recorded by the array microbarometers was used to estimate a yield of 21.6 (±5) tons TNT equivalent.We have demonstrated through joint seismo-acoustic analysis of the explosion that both the seismic velocity model and the atmospheric model are sufficient to explain the observed traveltimes.

A Tsunami Warning System for the Northeast Atlantic

L. Ottemoller, R.Luckett, B. Baptie and P. Whitmore

The risk to the UK from tsunamis is low, but not negligible, with possible source areas including offshore Portugal, the Mid-Atlantic ridge, and the Caribbean. In 2006, DEFRA commissioned the BGS to establish a system that can detect and discriminate earthquakes which could pose a tsunami risk to the UK. Until now, this is a feasibility study without being part of a 24/7 tsunami watch centre. The BGS chose to implement the EarlyBird software developed at the US NOAA West Coast and Alaska Tsunami Warning Center. A system comprising this software and a virtual network of more than 100 stations has now been operating reliably for over a year. The system is capable of automatically determining hypocentre location, various magnitudes and the moment tensor. However, from our testing it is clear that interactive monitoring of the system is required. We have added a new feature to EarlyBird to determine the energy-to-moment ratio in real-time, which can help to identify tsunami earthquakes. All results can be inspected and modified in real time using interactive tools. While knowledge of the moment tensor and energy-to-moment ratio can be useful in estimating the tsunamigenic potential of an earthquake, determination of these is not always robust and a decision matrix for sending out alerts has to primarily rely on location and magnitude. The detection level is lower than required, considering that tsunami generation requires earthquakes of magnitude over 6.5, and response times for alert messages are good. If a tsunami warning centre is set up within the UK we are confident that the system discussed here would fulfil the seismic requirements.

Tectonic implications of the 28 April 2007 MW4.0 Dover Straits earthquake

L. Ottemoller, B. Baptie and N. J. P. Smith

An earthquake of magnitude 4.3ML occurred beneath the town of Folkestone, southeast UK, on 28 April 2007 at 07:18 (UTC). The earthquake caused damage in Folkestone and was strongly felt across SE England. Estimated macroseismic intensites are as large as VI on the European Macroseismic Scale and the earthquake was the most damaging in the UK for some decades, with damage including chimney collapse and narrow cracks in brick masonry walls. Data from a strong motion instrument approximately 5km from the hypocentre suggest that peak ground acceleration (PGA) may have been as large as 0.1g. This was the largest earthquake in this region since a magnitude 4.4 ML earthquake in 1950. Significant earthquakes also struck the Dover Straits in 1776 and 1580; the latter had a magnitude of 5.7 ML and caused damage as far as London. The earthquake was well recorded on seismic stations across western Europe from Norway to Spain. We used both P- and S-wave arrivals at stations across Europe to determine the earthquake hypocentre. The epicentre is well constrained due to good azimuthal station coverage and a detailed knowledge of the shallow velocity structure near the epicentre, resulting in horizontal errors of +/-5km. The focal depth from travel time inversion is 5.3 +/- 4 km. Analysis of source spectra gives a seismic moment of 5.7x1014 Nm, a source radius of 0.5 km and a stress drop of 28 +/-24 bars. We determined a source mechanism for the earthquake by moment tensor inversion of broadband data at regional distances. The solution shows predominantly strike-slip faulting with a small normal component, resulting from either right lateral movement on a WSW-ENE striking fault plane or left lateral movement on a NNW-SSE striking fault plane. We find the lowest variance for a depth of 3km. We used two additional methods to constrain the source depth: (1) identifying and modelling pP observed at teleseismic distances, and (2) waveform modelling of the observations at the closest stations. The former gives a source depth of between 4 and 5 km, with a clearly observed pP phase at around 2 seconds after the initial arrival. The latter, though less well constrained suggests a source depth of around 3 +/-2 km.The regional tectonics of the Dover Straits area are dominated by Variscan structures with a predominantly NW orientation, which may suggest that NNW striking fault plane is the causative fault, re-activated by the overall regional stress regime. The axis of maximum compressive stress for this solution is roughly EW and in good agreement with other regional stress indicators. However, the relationship between this earthquake and seismicity in the Dover Straits remains unclear.

Tsunami earthquakes and slides

L. Ottemöller, R. Luckett and B. Baptie

Two previous studies commissioned by DEFRA have shown that the risk from tsunamis to the UK is low, but not negligible. Tsunamis originating in the Northeast Atlantic are rare, but cannot be ruled out. In response to this risk, DEFRA has commissioned a capability building project titled ‘Development of seismic methods to automatically identify tsunamigenic events and generate alerts’. This report describes work carried out during Phase 2 of the project: ‘Interpretational developments’ and deals with so-called tsunami earthquakes and submarine slides. These events are efficient in generating tsunamis and, therefore, of special concern. This may also be true in the UK where there is no risk from great subduction earthquakes that typically cause tsunamis. Tsunami earthquakes are defined as events producing a tsunami larger than predicted from their traditional magnitude. This is because they have a deficiency in seismic energy at higher frequencies, and can be identified by computing the ratio of energy to seismic moment. We developed and tested a module that computes the ratio of seismic energy to moment, which could be used in an operational tsunami warning centre. But as with other automatically determined parameters, the results need to be inspected by a seismologist. Submarine slides that can be triggered by earthquakes are known to cause tsunamis. The Storrega slide about 8200 years ago caused the largest known tsunami reaching the UK. Our interest here was to find out from previous case studies if submarine slides can be detected through seismic observations. In theory, it is possible to model the long-period seismic signal from slides, or inversely derive the slide direction and size from the seismic data. This has been shown to work for landslides at volcanoes. However, such a signal does not seem to be produced by all large submarine slides that cause tsunami. In many cases, the slide had been triggered by a large earthquake, and it has taken a considerable amount of work over many years to produce conclusive results on which of the two caused the tsunami. It, therefore, appears not feasible at the moment to detect submarine slides through seismic methods. There is a difference in the excitation of T-waves (acoustic energy trapped in the SOFAR channel) between tsunami earthquakes and submarine slides. Submarine slides can be efficient sources of T-waves while tsunami earthquakes usually release little energy in form of T-waves. However, using this information in real-time may be problematic as the observation of T-waves at seismic stations is highly variable, and not all slides and tsunami earthquakes have the same characteristics. The risk from submarine slides is probably still too poorly understood and may deserve more attention.

Seismic velocity structure of the island of Montserrat from reflection/refraction tomography

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The Soufriere Hills Volcano (SHV) on the island of Montserrat, Lesser Antilles, resumed its activity in 1995 and has since been studied in great detail, but knowledge of its deep structure is scarce. In December 2007 the SEA-CALIPSO land-sea seismic experiment was conducted to investigate the seismic velocity structure of the island and better understand the magma system feeding the volcano. An array consisting of 28 3-component Refteks, 209 1-component Texans and 10 LC-2000 Ocean Bottom Seismometers (OBSs) was installed to record the signals generated by an array of 8 airguns firing every 60 s at a pressure of 2000 psi and with total volume of 2600 cubic inches. A total of 4414 shots were recorded over 77 hours. The survey covered an area of about 50 × 40 km. A subset of the data, consisting of four OBSs and four land stations on a south-east to northwest line, has been processed and travel times have been inverted to obtain a two-dimensional seismic velocity section through the island. Identified phases include crustal and sediment P-waves and their multiples, basement reflection and reflection from a shallow sediment layer. A regularized inversion approach has been used, where the data misfit and the model roughness are minimized simultaneously to give a minimum-structure model. The inversion process starts with a highly smoothed model on a regular grid and uses a layer stripping approach. The resulting velocity model reveals the presence of a high velocity body with velocity contrast of up to 1.5 km/s underneath the island, about 10km wide and extending from the surface to a depth of 8.0 km. This could be explained by the presence of intrusions. The basement reflector is observed at a depth of about 1200 m, presenting a depression under the island due to edifice loading. In the superficial layer observed velocities vary from 1.6 to 3.0 km/s at sea and from 3.0 to 4.5 km/s on land. A shallower reflector is observed at about 500m depth possibly marking the unconformity between Soufriere Hills and the older volcanic edifices. The results so far provide a constraint on the upper crustal structure up to a depth of 9km that will help understand volcanism at Montserrat and other island arc volcanoes.

The 2 February 2008 Svalbard earthquake: Relative location of the aftershock sequence and seismotectonic interpretation

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A strong earthquake with a preliminary moment magnitude of about 6.0 occurred in Storfjorden off Svalbard, on 02:46 UTC 21st February 2008. The source of the event was located in the lower crust, approximately 85 km from Hornsund and 155 km from Longyearbyen. The USGS double-couple fast moment tensor solution describes normal-oblique strike-slip faulting. The sea region around Bear Island, situated south of Svalbard, constitutes the target area of an International Polar Year project that studies the continental margin, including deployment of new high-quality broadband instruments. The above mentioned earthquake, as well as the vast number of aftershocks that followed, were recorded by a number of seismic stations in the region. The geographic distribution of these stations, (Hornsund - HSP, the Spitsbergen array - SPITS, Hopen Island - HOP, Bear Island - BJO, and Ny Aalesund - KBS) enables the recording and analysis of the aftershock sequence. Array-based waveform correlation techniques applied to Spitsbergen array data provide an image of the clustering within the aftershock sequence. The addition of the 3-component single stations forms the basis for high accuracy relative location of the recorded events and the detailed mapping of their spatial distribution. When combined with the fault slip inversion results, the aftershock distribution provides a unique opportunity to study the details of the source rupture process. There are several potential factors that could explain the event, namely plate related forces, stresses related to lateral variations in crustal structure, and erosion and sedimentation processes. The EW maximum compression expressed by the moment tensor solution is a characteristic that has been observed before in the region.

A Comparison of Two Recent Damaging British Earthquakes

S.L. Sargeant, L. Ottemöller and B. Baptie

We compare two damaging moderate size earthquakes that occurred in the UK. The first occurred near the town of Folkestone on the southeast coast of Britain on 28 April 2007 with a moment magnitude of 4.0. The earthquake was shallow at about 5 km. The event caused considerable damage near the epicenter and was felt throughout south-eastern England. The second earthquake was slightly larger with a moment magnitude of 4.5 and occurred on 27 February 2008 in Lincolnshire (eastern central England). This earthquake was a lot deeper at about 20-25 km. Incidences of damage were sporadic but observed over a relatively wide area and the earthquake was felt over much of the UK. For both earthquakes we were able to invert for the moment tensor using regional broadband data. Both mechanisms are predominantly strike slip and consistent with the regional stress pattern. The main difference between the two earthquakes is the depth, and the two earthquakes could represent the two end-members in terms of source and ground motion characteristics of British earthquakes. We determined stress drop and rupture dimen¬sions for each event by modelling the source displacement spectra. We find that the deeper earthquake is charac¬terized by a significantly higher stress drop. This corresponds to a larger slip relative to the shallower earthquake, while the fault area is about the same for the two events. Since stress drop controls the strength of high frequency radiation and therefore peak ground acceleration, the two earthquakes represent contrasting ground motion sce¬narios. However, the ground motion observations are limited and affected by the influence of site effects.

Observations from the Folkestone, U.K., Earthquake of 28 April 2007

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Earthquakes in Britain are usually minor with respect to damage. However, the Folkestone earthquake (ML 4.3, Mw 4.0), which occurred on the southeastern coast of England (Figure 1) on 28 April 2007 at 07:18 UTC (08:18 BST) caused significant damage. One person was injured by falling masonry, and the Shepway District Council invoked emergency procedures to deal with the effects of the earthquake. This is the first time that emergency procedures have been invoked for a British earthquake. Approximately 60,000 homes lost power for 85 minutes due to tripping of two high-voltage transformers. The epicenter of the earthquake, latitude 51.102°N and longitude 1.169°E (Ottemöller et al. forthcoming), locates very close to Folkestone (Figures 1A–C). Ottemöller et al. (forthcoming) determine a depth of around 6 ± 3 km from United Kingdom (UK) and European short-period and broadband data. The focal mechanism, shown in Figure 1C, indicates normal faulting with a significant component of strike-slip on either a north-northwest to south-southeast trending or east-northeast to west-southwest trending plane (Ottemöller et al. forthcoming). The earthquake was followed by nine after-shocks (ML 1.0–1.8), which occurred up to 5 May 2007. None of these were felt. A compendium of observations from the Folkestone earthquake is presented here. This includes analysis of the first "strong-motion" record from a British earthquake, a description of the damage, an investigation of how the distribution of damage may relate to the distribution of unconsolidated deposits, and the results of the macroseismic survey for the earthquake. Assignment of maximum intensity, and its spatial extent, provoked a lively debate among the authors, which is also documented here.

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Rotational Earthquake Effects in the United Kingdom

S. Sargeant and R.M.W. Musson

The United Kingdom is an area of low to moderate seismicity, and damaging earthquakes are uncommon. However, even in the limited record of damage from historical British earthquakes, a number of instances can be found of rotational effects on parts of structures, primarily chimneys or the tops of spires. We have assembled all the instances we know of from the United Kingdom record and present them here with illustrations and extracts from the original reports. It is not possible to determine whether these are the effects of true rotational motion or the effects of translatory shaking. Interestingly, this problem was considered in some detail by field investigators as long ago as the 1880s.