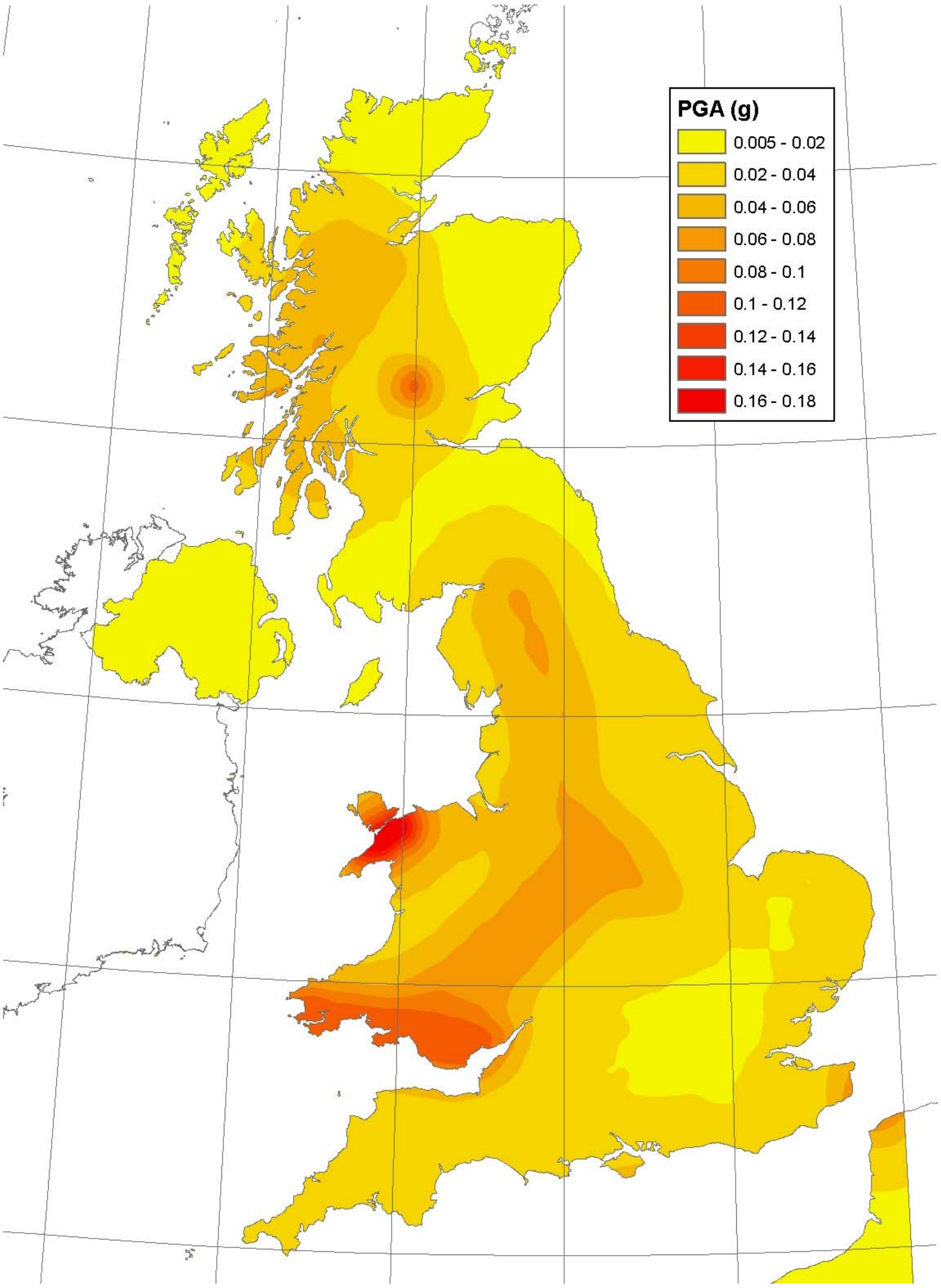
UK Earthquake Monitoring 2007/2008

BGS Seismic Monitoring and Information Service

Nineteenth Annual Report



BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT OR/08/072

UK Earthquake Monitoring 2007/2008

B. Baptie (editor)

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PGA seismic hazard map for a 2,500 year return period, from Musson and Sargeant (2008)

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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 19th year of the project, five new broadband seismograph stations were established, giving a total of nineteen broadband stations. Real-time data from all broadband stations are being transferred directly to Edinburgh for archival and storage. Near real-time data from broadband stations operated by a number of partner agencies in northern Europe have also been incorporated into our automatic data processing system to improve detection and location capability in offshore areas, particularly the North Sea. Upgrade of the monitoring network remains our primary goal. We have purchased a further ten broadband sensors and high dynamic range digitisers.

Both the largest British earthquake in 25 years (Market Rasen, 5.2 M_L) and also the most damaging British earthquake in many decades (Folkestone, 4.3 M_L) occurred in 2007/2008. Local authorities invoked emergency measures for the latter. As a result of improvements in both data acquisition and data processing made over the last few years, data of unprecedented quality and quantity was collected for both these earthquakes. This included both digital waveform data and also near real-time macroseismic data.

Nine papers have been published in peer-reviewed journals and seven presentations were made at international conferences. Eight BGS internal reports were prepared along with two confidential reports. Two PhD studentships, partially funded by the project, were completed.

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 programme, 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 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 2007

Introduction

Monitoring Network

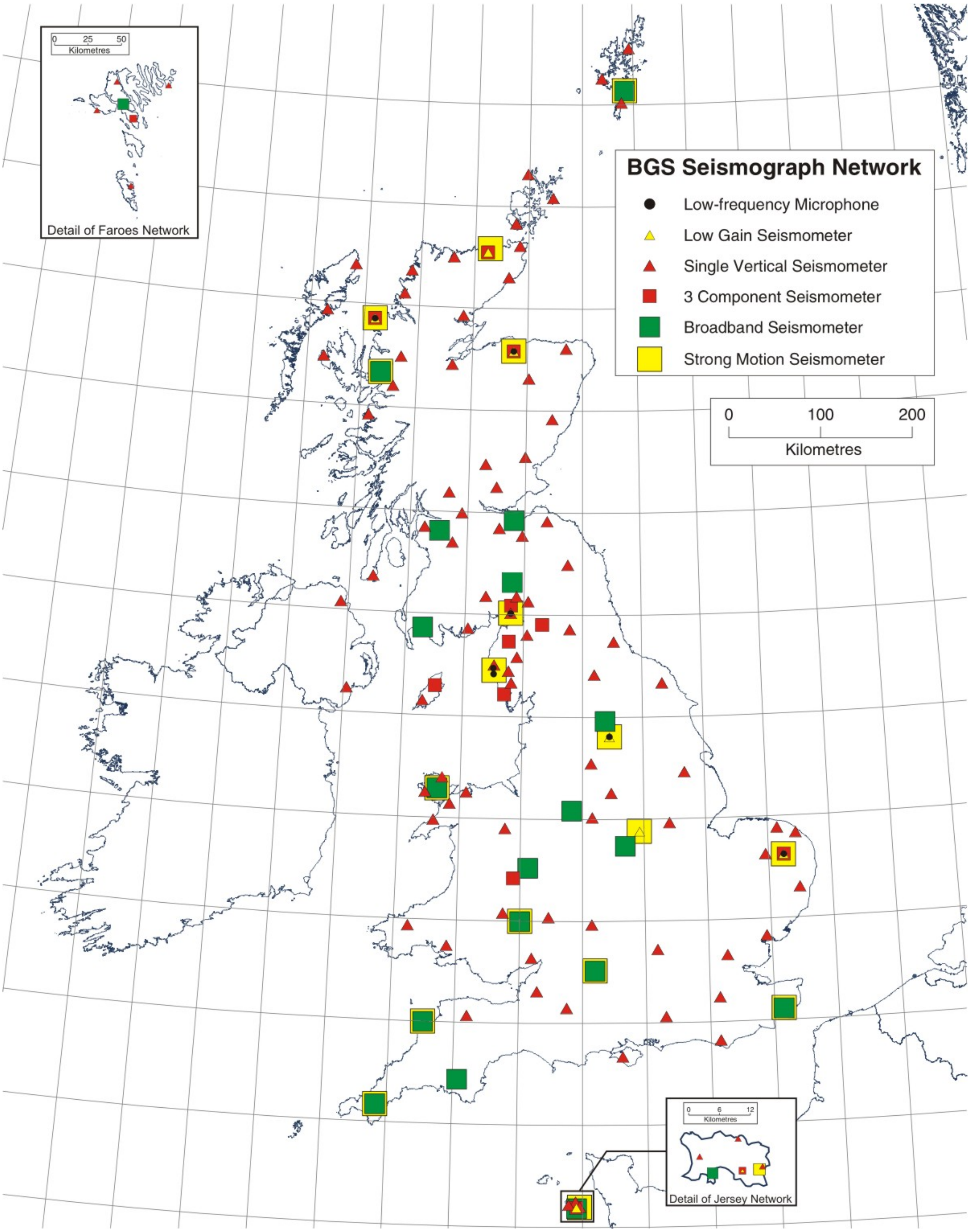
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. By the late nineties, the number of stations reached its peak of 146 stations, with an average spacing of 70 km. We are now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

By the late nineties, the number of stations reached its peak of 146, with the network 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 is 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 are 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 nineteen broadband sensors at stations across the UK.



BGS seismograph stations, March 2007

Achievements

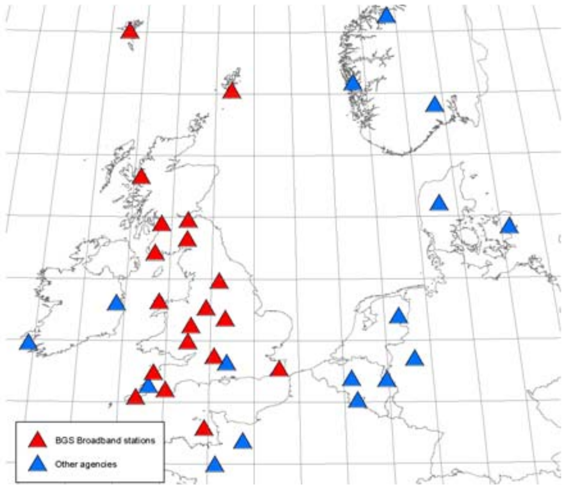
Network Development

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: Carmenellis (Cornwall), Folkestone (Kent), Long Mynd (Shropshire), St. Aubins (Jersey) and Sornfelli (Faroes). Continuous data from all five 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 nineteen.

Work is almost complete on a new broadband station in Kent and construction work is underway for a new broadband station near Keswick (Cumbria). In addition, we have carried out site surveys for new broadband stations at Drumtochty, Aberdeenshire and Allenby, Northumberland.

Ten new broadband seismometers, along with high dynamic range data acquisition, were purchased during the year 2007-2008. These will be deployed either at existing or new stations as part of our network development program. We also purchased ten 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.

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 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.

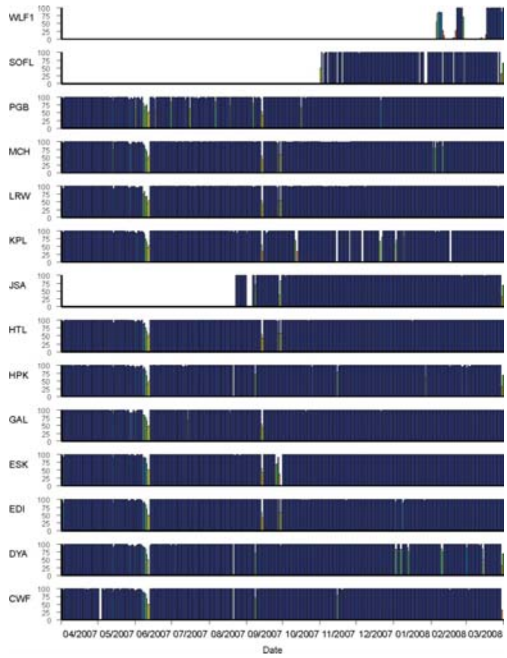
We have increased the flow of real-time data from seismic stations operated by European partner agencies into our near real-time processing. These include data from Belgium, Denmark, France, Ireland, the Netherlands and Norway. The use of these data greatly improves our detection capability in offshore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

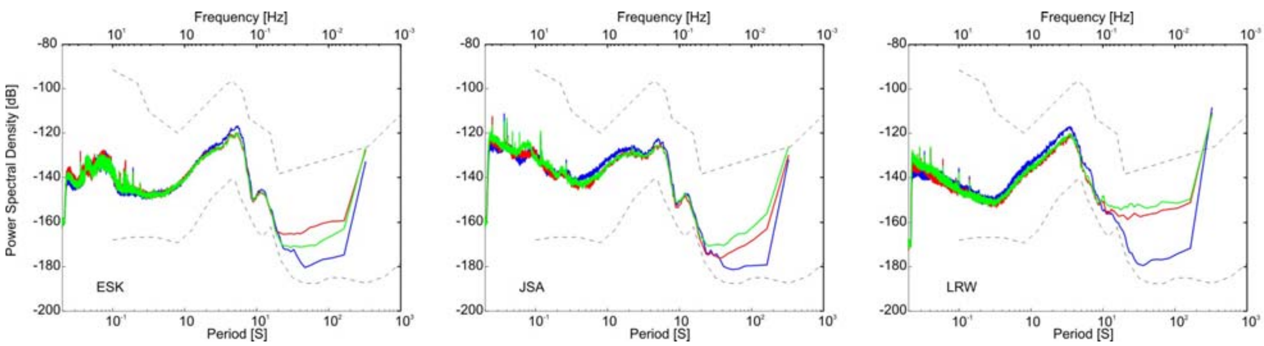
EarlyBird, as used by the US West Coast and Alaska, Pacific and the Caribbean Tsunami Warning Centres, is an extension of Earthworm, and has been implemented at BGS for real-time detection and location of significant seismic events in the Atlantic region. The system has been under test since the end of 2006, using near real-time data from seismic stations from around the North Atlantic region, and has successfully issued automatic warnings for many events. Of particular interest, were the Folkestone and Market Rasen earthquakes: automatic locations for these earthquakes were within a few kilometres of the final location and warnings were issued by email and SMS within minutes of the origin times.

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 and this is the first time we have been able to gain an accurate picture of network performance. In general, we find that the data from all broadband stations are over 98% complete. Data losses result from failure of outstation hardware, communications problems, or failure of central data processing. For example, data loss at the beginning of June 2007 resulted from the failure of central data acquisition hardware. 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.

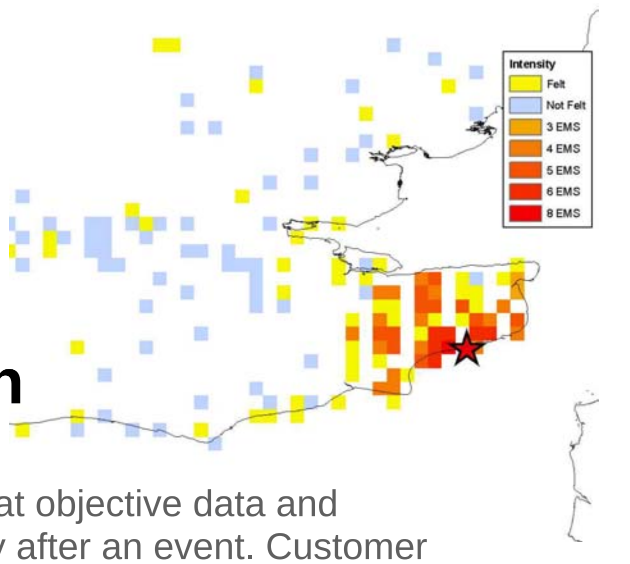


Data completeness for selected broadband stations for April 2007 to March 2008. Completeness is shown as a percentage of total time.

In addition, we are also able to monitor the performance of our broadband stations by analysing noise levels at individual sites, which can then be compared alongside commonly used noise-models.



Power spectral density estimates for each calculated from background noise recordings from broadband stations at Eskdalemuir, Jersey and Lerwick. Median values are shown by blue, red and green lines, for vertical, north-south and east west components of ground motion respectively. The dashed lines show the low and high noise models given by Petersen (1993).



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, five of which were of a suspected sonic origin and one was for an explosion, and for 24 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, two enquiries were received from Nuclear Power Stations after alarms triggered, and a response was given within 15 minutes in both cases.

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 Folkestone and Market Rasen earthquakes. For the latter, an online macroseismic questionnaire was made available via the BGS "Earthquakes" website within 30 minutes of the event occurring. 1,600 completed questionnaires were received within the first twelve hours of going online with a further 18,400 received by 12:30 on 3 March.

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 2007, it was issued in June 2008.

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 student at the University of Leicester has completed a PhD using arrival time data from earthquakes recorded on British Geological Survey (BGS) seismic stations to develop a 3-D model of seismic velocity beneath England and Wales. The 3-D model highlights small and large scale structural variations within the crust and uppermost mantle at unprecedented resolution compared to existing models. One of the main features is a high P-velocity body at the base of the crust underlying the East Irish Sea Basin consistent with magmatic underplating in response to Paleocene mantle plume activity.

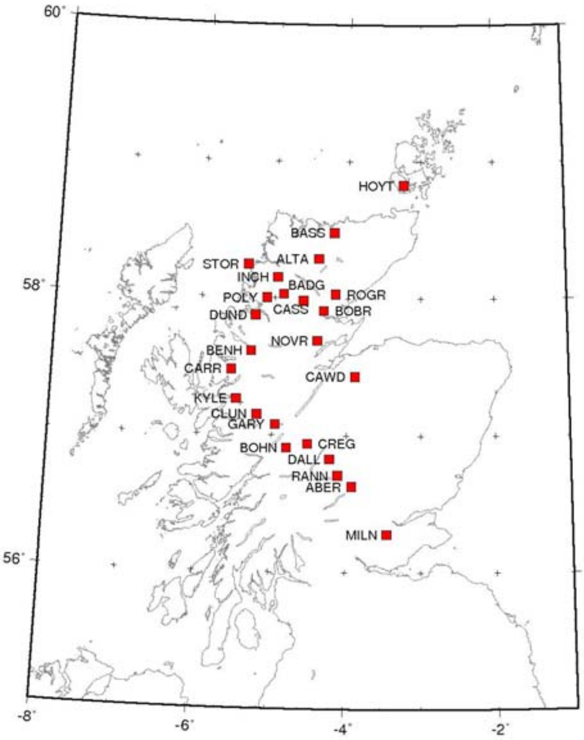
The study uses a subset of 1038 well located events from the BGS digital catalogue from 1982 onwards, distributed between 51 and 55 degrees north, and consisting of 12,238 P- arrivals and 5,898 S- arrivals. Seismic travel times are inverted simultaneously for V_p, V_p/V_s and hypocentre parameters using the SIMULPS code (Thurber 1983; Evans et al. 1994) on a series of grids. Resolution estimates indicate the model is most reliable at mid-crustal depths beneath Wales and North-West England.

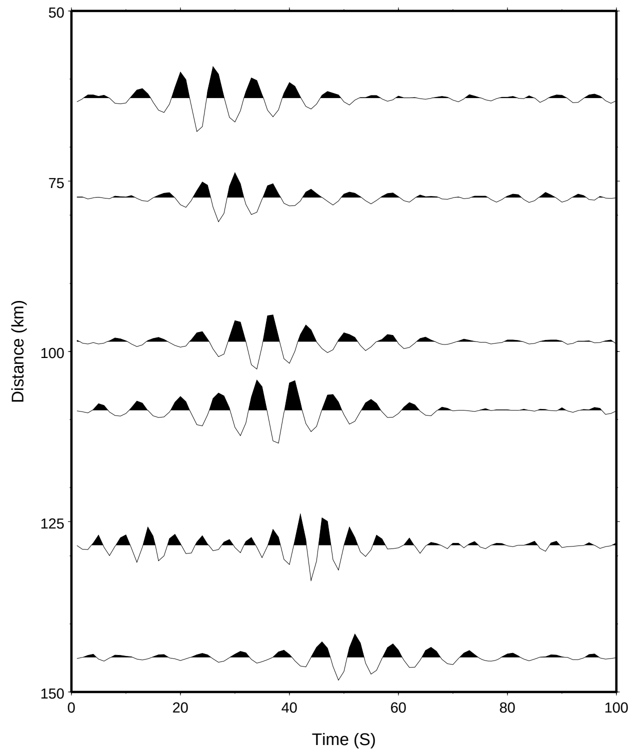
Depth slices and vertical profiles through the region of underplating show that regions in the lower crust have a P-velocity in excess of 7.2 km/s. A secondary body, which also looks intrusive, is identified above the thickest part of the underplate and directly underlies the region of maximum inferred Cenozoic denudation in the East Irish Sea. Interestingly, a belt of earthquakes is observed on the eastern and southern margins of the underplated region.

A BGS CASE student at the University of Liverpool has completed a PhD that used earthquakes recorded on BGS stations to study source, path and site effects using *Q* tomography. Over 3200 records from 273 events ($2.0 > M_L > 4.7$) from 1992 to 2006 were used in the inversion scheme to determine the quality factor *Q*, seismic moments and stress drops.

The results suggest a frequency independent, depth dependent Q structure. A linear relationship proportional to 0.7 M_L between moment magnitude (Mw) and local magnitude (M_L) is found in the range of 2 to 4.7 M_L. Most stress drops are found to be between 0.1 and 10 MPa, with no evidence for increasing stress drop with magnitude. A multiple segment attenuation 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 signal window.

Site response functions are found to broadly correlate with regional geology, mean amplification occurring in the Cenozoic sedimentary rock sites in the south east of England and mean deamplification occurring in the harder





Stations deployed as part of the “Reflectors Under the Scottish Highlands (Ascencio et al, 2003) project (left) and surface wave Green’s functions (right) calculated by cross-correlation of ambient noise recorded at station MILN with five other stations in the profile running across Scotland from the southeast to the northwest.

Palaeozoic rock sites of Wales and Scotland.

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.

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 Greens 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.

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 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. Data along a transect extending roughly east-west across the British Isles from East Anglia to central Ireland is being collected from permanent BGS broadband stations and temporary deployment of broadband sensors at both new and existing sites. This research is expected to lead to a significant improvement in our understanding of the root causes of uplift in the UK.

INGV, Milan, GFZ, Potsdam, and BGS have continued to work together on developing the application of the EMS intensity scale. INGV Bologna/Rome and BGS have also worked together on the Eurosismos project to make major seismological archives digitally available to a wide community. This is complemented by ongoing collaboration with a wide range of international institutes on surveys of extant seismological archives, in the framework of the IASPEI Working Group on Seismological Archives.

The European Mediterranean Seismological Centre (EMSC) and BGS have collaborated on development of online macroseismic surveys.

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 is working with the University of Bergen, analysing the 7 January 2007 Viking Graben earthquake, the 21 February 2008 Svalbard earthquake and also on monitoring seismicity in the North Sea.

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

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 42 events were supplied 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.

Macroseismic data was also been exchanged with other agencies after the Folkestone and Market Rasen earthquakes.

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 formal launch of the BGS "School Seismology Project" took place on the 30th May 2007 at the Institute of Physics in London. This project builds on a learning award from the National Endowment for Science, Technology and the Arts (NESTA) and aims to improve interest in the physical sciences among students at GCSE level by tapping into their interest in earthquakes.

The first aim of the project, to develop specific resources for teaching and learning seismology in UK schools, has now been achieved. These take the form of a booklet of classroom activities entitled "Seismology : Innovations in practical work", published by the Science Enhancement Programme (SEP) associates scheme, which are distributed free of charge to teachers in the UK. Over 2,500 booklets have now been distributed. A set of very inexpensive simple practical equipment items to support these activities will be marketed through Middlesex University Teaching Resources (MUTR). In addition support materials and resources have been made freely available to teachers through the BGS website.

The second aim of this project was to contribute to the development of 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 real investigations using their own data.

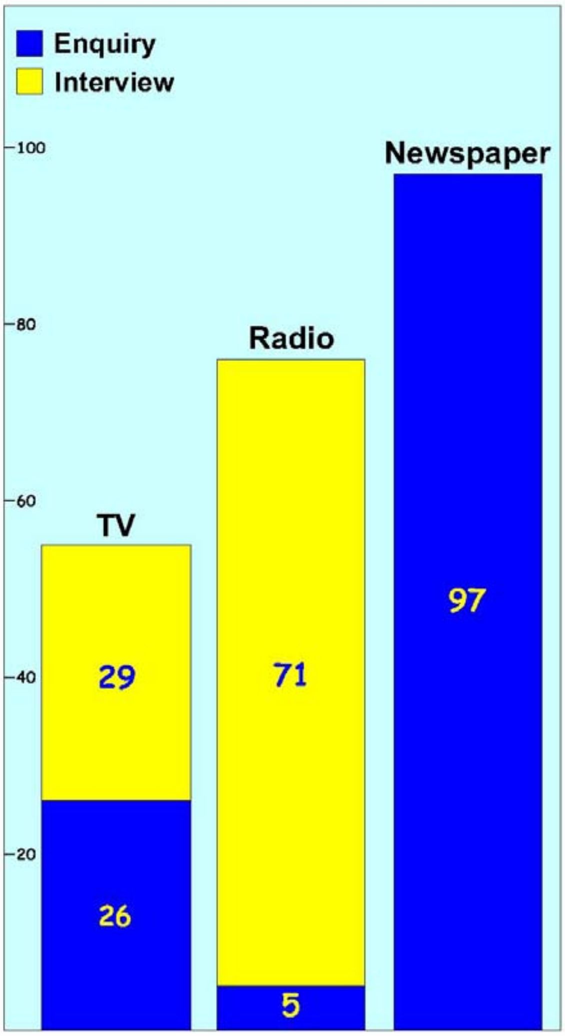
The seismometer is now available through MUTR and a total of 143 have been purchased. Commercial support for the project resulted in over £18,000 that allowed us to distribute seismometers to interested schools free of charge. In addition, we also provided training for teachers from 62 schools at BGS organised events. We also have now signed 12 partnership agreements with university earth science departments who are committed to promoting the project locally.

BGS has developed a simple online database that allows schools across the UK to exchange data for different earthquakes.

A number of lectures and presentations were given to schools, university students and other interested parties. The BGS Open Day attracted 685 visitors with many of them visiting the interactive earthquake display. A further 180 school pupils (inc teachers) from 8 different schools visited during the following Schools Week.

The seismology web site continues to be widely accessed, with over 520,000 visitors logged in the year (almost 12 million hits). Significant peaks were observed in April 2007 and February 2008 when over 14,000 visitors were recorded on 28 April 2007, following the Folkestone earthquake and over 80,000 visitors were recorded on 27 February 2008, following the Market Rasen earthquake.

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 2007-2008, 814



enquiries were answered. Some 228 of these were from the media, including 131 for TV and radio broadcasts following significant earthquakes. The broadcasting enquiries led to 29 TV and 71 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 2007, published and distributed in June 2008 (Galloway, 2008).

There were 111 local earthquakes located by the monitoring network during the year, with 38 having magnitudes of 2.0 M_L or greater, twelve having magnitudes of 3.0 M_L or greater and four having magnitudes of 4.0 M_L or greater. Thirteen events with a magnitude of 2.0 M_L or greater were reported felt, together with a further 23 smaller ones, bringing the total to 36 felt earthquakes in 2007.

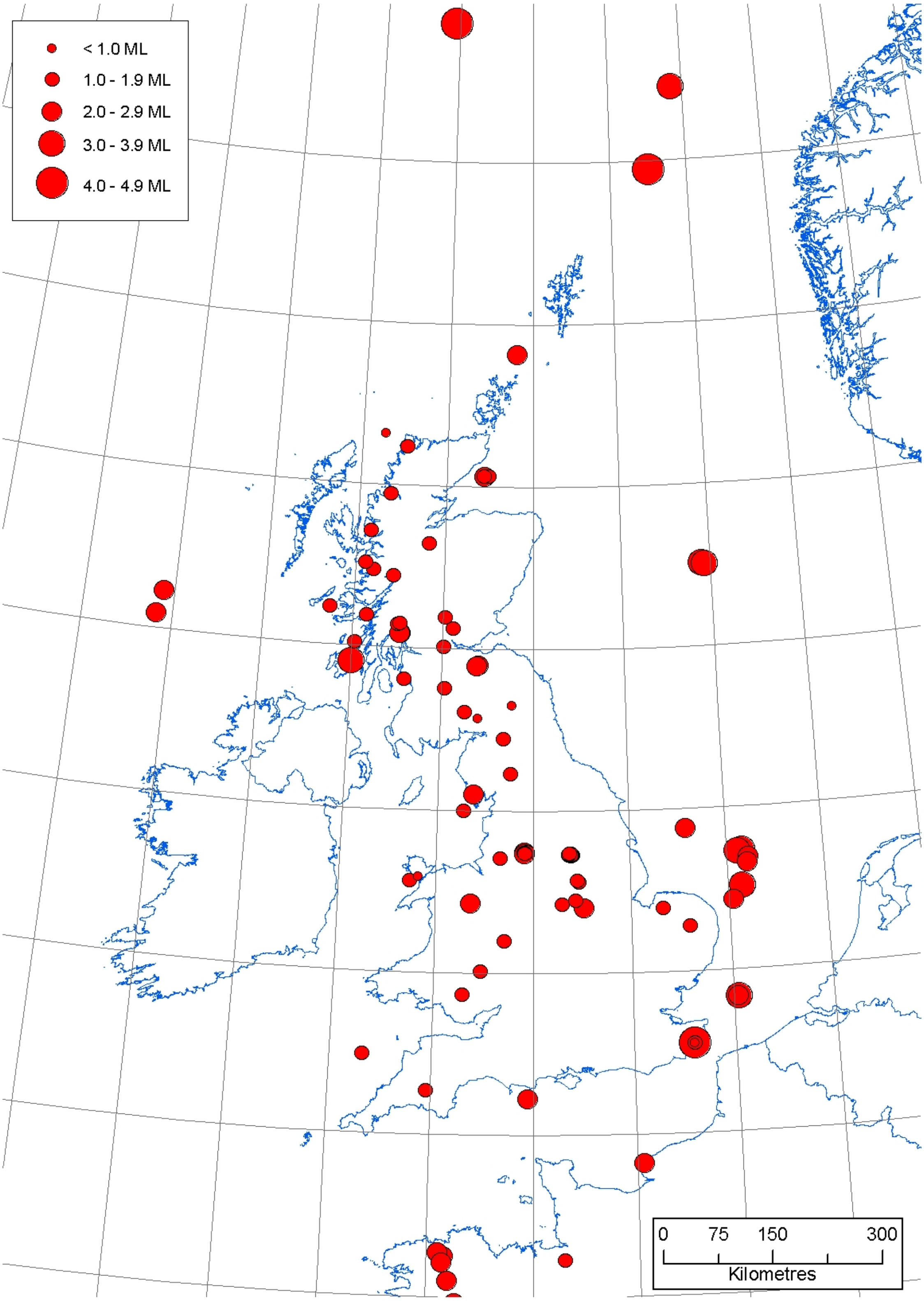
The largest onshore earthquake of the year with a magnitude of 4.3 M_L occurred in Folkestone, Kent on 28 April at 07:18 UTC, at a depth of about 5 km. In parts of Folkestone, where the highest observed intensity was 6 EMS, many houses suffered minor structural to chimneys and walls.

The largest offshore earthquake occurred in the Norwegian Sea on 7 January, with a magnitude of 4.8 M_L. It was located approximately 230 km northeast of Lerwick, Shetland Islands. A further 15 events occurred in the North Sea and surrounding waters during the year, with magnitudes ranging between 2.0 and 4.4 M_L. Two of these events occurred in the Northern Atlantic Ocean, approximately 170 km northwest of Ireland, on 17 June and 21 July, with magnitudes of 2.2 and 2.7 M_L, respectively. These are the first earthquakes in the area since a magnitude 2.9 M_L event on 19 December 1986 and before that a 3.3 M_L event on 13 April 1980.

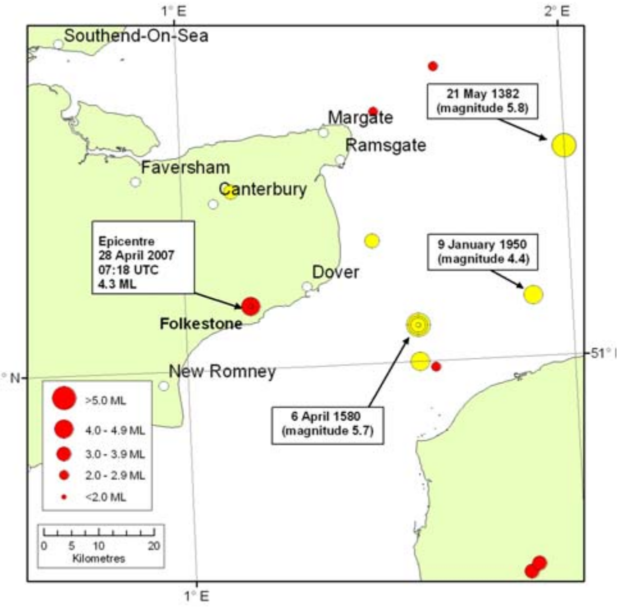
The spatial distribution of seismicity in 2007 generally reflects that observed in the instrumental catalogue as a whole, with the majority of earthquakes occurring in and around Wales, Cornwall, the Midlands, Cumbria and the Scottish Borders and in western Scotland. There was also activity in the northern and southern North Sea.

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 2007 to March 2008, a total of 516 teleseismic earthquakes were detected and analysed.

In the following sections, we provide more detailed reports of the magnitude 4.3 M_L Folkestone earthquake (2007), and the magnitude 5.2 M_L earthquake near Market Rasen (2008). We also summarise some of the destructive earthquakes that have occurred around the world throughout the year.



Epicentres of all UK earthquakes detected in 2007.



Seismic Activity

Folkestone, 28 April 2007

The most damaging British earthquake in many decades struck Folkestone on 28 April 2007 and resulted in the emergency measures being invoked by local authorities. The earthquake was widely felt across southeast England, with estimated macroseismic intensities as high as 6 EMS.

An earthquake of magnitude 4.3 M_L 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 were as large as 6 EMS 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 5 km 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 M_L earthquake in 1950 and there had been little instrumentally recorded activity in this area. However, significant earthquakes struck the Dover Straits in 1382 and 1580; both had magnitudes of around 5.7 M_L 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 +/-5 km. The focal depth from travel time inversion is 5.3 +/- 4 km.

The PGA observed from the mainshock of 0.1 g is the largest ever recorded from an earthquake in the UK. While this acceleration level was only maintained for a very short time, it may have been sufficient to explain the damage observed in Folkestone. Given that the distance between source and the TFO site is between 5 and 8 km, it is possible that high accelerations were also observed in Foord district of Folkestone, where most damage was observed, and is at a similar distance from the epicentre.

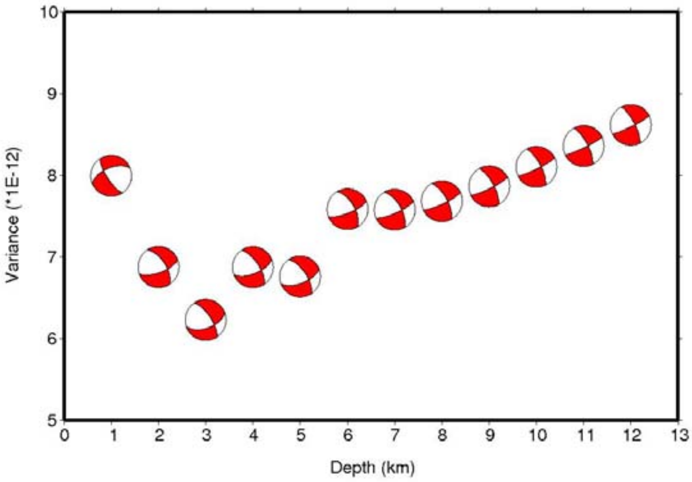
We used the Nakamura or H/V spectral ratio technique (Nakamura, 1989) to empirically estimate the site response, by computing the horizontal to vertical (H/V) spectral ratio from microtremor recordings. Peaks in the H/V ratio can then be related to the fundamental frequencies at which amplification could occur. Applying the method at station TFO we find significant site amplification at frequencies of 0.4 and

3.9 Hz. Another less significant peak at 17 Hz may have contributed to the PGA of 0.1 g at a frequency of 14.3 Hz. While the site conditions in Folkestone will be somewhat different from TFO, the geology is similar enough to suggest that site amplification has contributed to the observed damage.

Analysis of source spectra gives a seismic moment of 5.7×10^{14} Nm, a source radius of 0.5 km and a stress drop of 28 ± 24 bars.

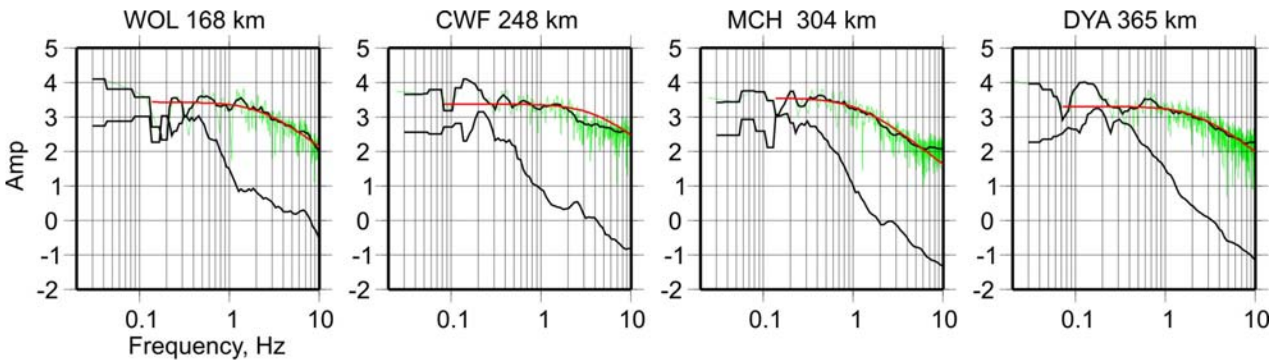
We determined a source mechanism for the earthquake by moment tensor inversion of broadband data at regional distances. The solution shows predominantly strike-slip faulting with a small normal component, resulting from either right lateral movement on a WSW-ENE striking fault plane or left lateral movement on a NNW-SSE striking fault plane. We find the lowest variance for a depth of 3 km.

In addition to the source depth estimates from both travel-time and moment tensor inversion, 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. From these four independent estimates, we conclude that the source is indeed shallow, which is consistent with the highly localised damage and other macroseismic data.

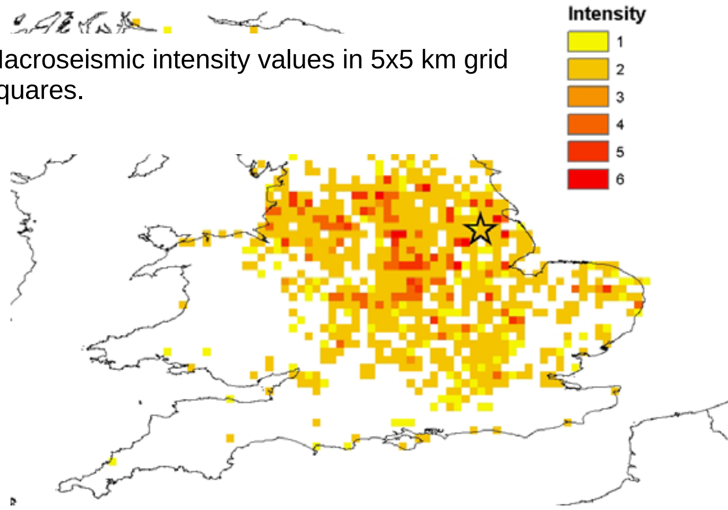


Variance as a function of depth for a range of fixed depth estimate moment tensor inversions using regional broadband data from the Folkestone earthquake.

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.



Modelled and observed source spectra for the Folkestone earthquake.



Macroseismic intensity values in 5x5 km grid squares.

Seismic Activity

The Market Rasen earthquake of 27 February 2008

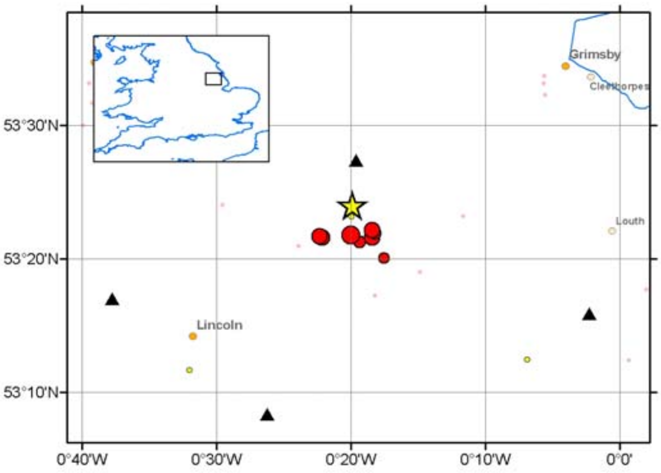
The largest UK earthquake in over 25 years struck just before 01:00 GMT on 27 February 2008. The epicentre was approximately 4 km north of Market Rasen, but the earthquake was widely felt across the British Isles, with the most distant reports coming from Aberdeen, Truro, Ireland and Liege. BGS also received reports of damage to chimneys and masonry over a widespread area. The magnitude of the earthquake is estimated at 5.2 M_L

The Market Rasen earthquake was the largest earthquake in the UK since a magnitude 5.4 M_L earthquake struck North Wales in 1984. Earthquakes of this size occur in the UK roughly every 30 years. The earthquake location was determined by inversion of over 100 phase readings from the UK and neighbouring countries. The best-fitting solution gave the epicentre 4 km north of Market Rasen and a focal depth of 18 km, and used 62 phases. The errors in the north-south, east-west and vertical directions were 8.3 km, 5.6 km and 13.8 km, respectively.

Data from over 30,000 questionnaires, collected online, were used to determine how widely the earthquake had been felt, with the most distant reports coming from Aberdeen, Truro, Ireland and Liege, Belgium. The results show isolated values of 6 EMS at 59 locations, widely scattered over England in an area roughly between York and Nottingham, and east of Manchester. Processing the isoseismals to yield macroseismic parameters for the earthquake (Musson 1996) gives a magnitude of 5.2 M_L and a depth of 25-30 km.

BGS received reports of damage over a widespread area. However, an immediate survey of the epicentral area, carried out by a BGS team in the 48 hours after the earthquake, found that the damage was mainly to the tops of chimneys on Victorian terraces (bricks and pots dislodged) and secondary damage to roofs caused by falling debris. Some of these chimneys appeared to be in a poor condition with old mortar. There was some evidence that the area of maximum damage in Gainsborough, was confined to an area underlain by relatively soft river terrace and glacio-fluvial deposits.

Modelling of regional and distant recordings of the earthquake suggests that the focal depth was between 20-25 km below the surface. This depth is consistent with both the macroseismic data and results from travel-time inversion.

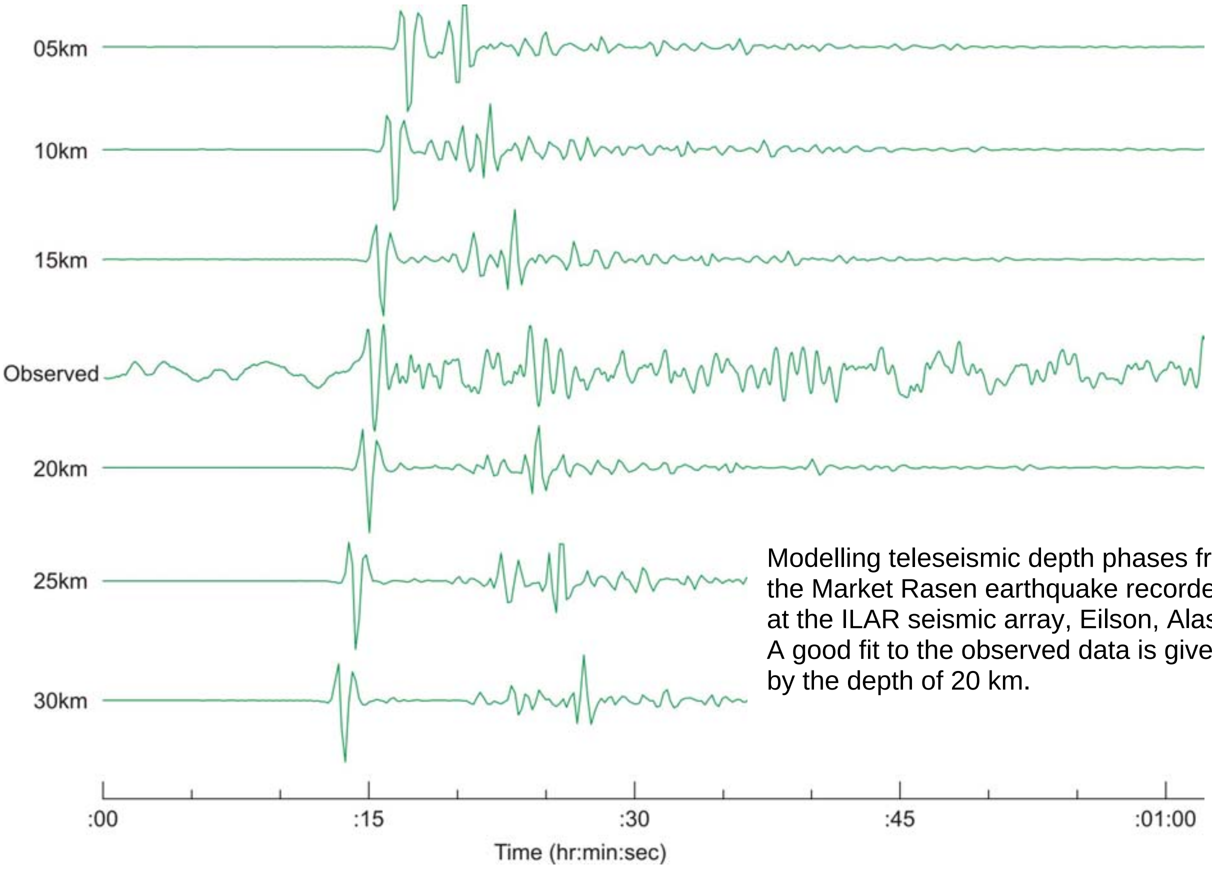


Epicentres of the Market Rasen mainshock (star) and aftershocks (red circles). Temporary stations deployed to record aftershocks are shown by black triangles.

The best-fitting fault plane solution, computed from inversion of regional data, shows predominantly strike-slip faulting on a near vertical fault, striking either east west or north south, which is consistent with maximum compression in NW-SE direction.

The moment magnitude of 4.4 is considerably smaller than the M_L value of 5.2. This discrepancy has been observed for other UK earthquakes (e.g., Dudley 2002; Folkestone 2007). The moment magnitude scale reflects the physical dimensions of the earthquake rupture and the amount of slip during the event. By contrast, the local magnitude is a measure of the high frequency radiated energy from the earthquake, and may be in keeping with an observed high stress drop and peak ground accelerations for this earthquake.

A BGS team deployed four temporary instruments within 48 hours of the earthquake to detect small aftershocks. As a result we were able to detect nine aftershocks, a number of which would not have otherwise been detected. The largest had a magnitude of 2.7 M_L and was felt locally.The epicentres of the aftershocks are tightly clustered, just south of the mainshock. The observed alignment of the aftershock epicentres in an east-west direction may suggest that this is the more likely fault orientation, however, this scatter may also be caused by phase reading errors.



Modelling teleseismic depth phases from the Market Rasen earthquake recorded at the ILAR seismic array, Eilson, Alaska. A good fit to the observed data is given by the depth of 20 km.

Seismic Activity

Global Earthquakes

There were four ‘great’ earthquake (magnitude over 8.0), fourteen ‘major’ earthquakes (magnitudes between 7.0 and 7.9) and 175 ‘strong’ earthquakes (magnitudes between 6.0 and 6.9). These numbers are similar to the long-term averages for these magnitude ranges, which are, one, seventeen and 134, respectively.

At least 514 people were killed and 1090 injured when a magnitude 8.0 earthquake struck the coast of Peru, 145 km south-southeast of Lima on 15 August 2007. More than 35,500 buildings were destroyed and many more damaged. Damage and casualties were concentrated in Chincha Alta, Ica and Pisco. Most of the buildings destroyed were of adobe construction although there was also significant damage to hospitals, schools, clinics and many other large public buildings. Widespread communications and power outages occurred in the area. The Pan-American Highway and other main transport routes suffered heavy damage due to landslides and cracks. The earthquake also resulted in a tsunami that was widely observed around the Pacific.

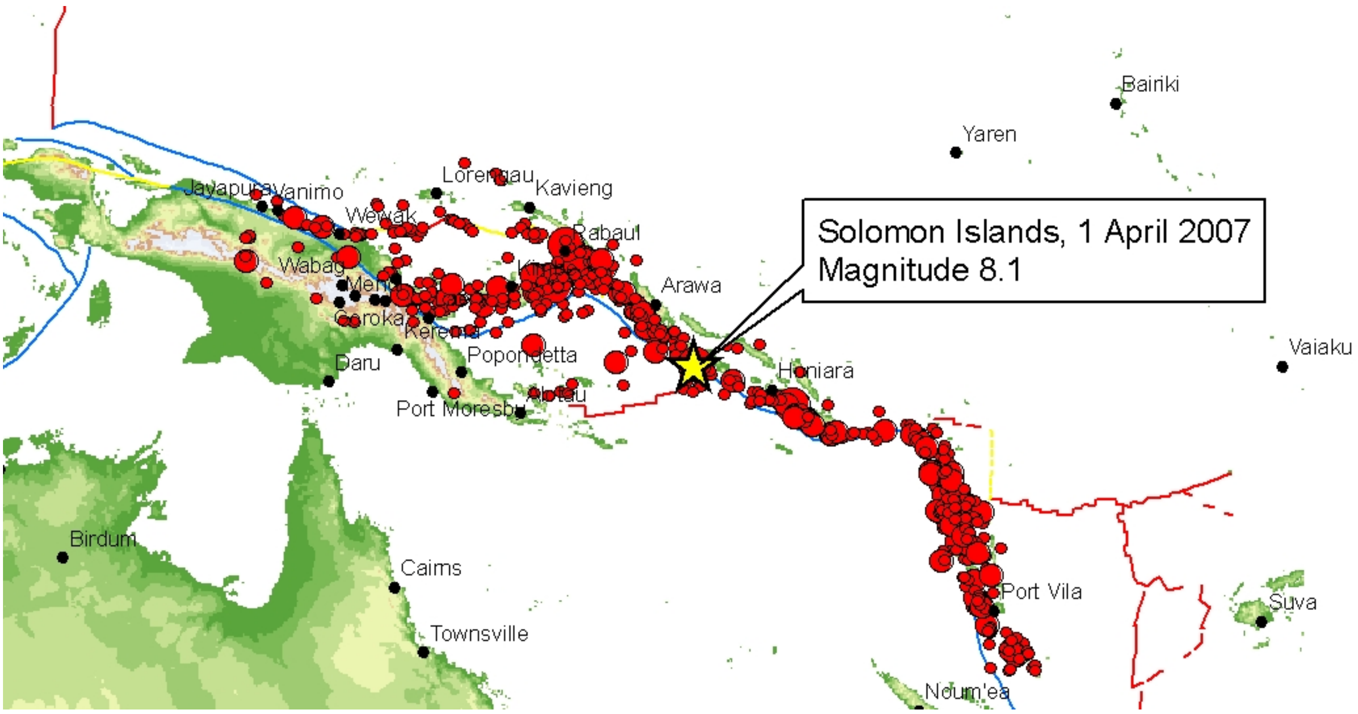
The seismicity of Peru is related to subduction of the Nazca plate beneath the over-riding South American plate. The two plates are converging at a rate of 77 mm per year. In this case, the earthquake resulted from thrust-faulting on the interface between the two plates, with the South American plate moving up and seaward over the Nazca plate.

The largest earthquake during the year, with a magnitude of 8.4 Mw, occurred on 12 September and was the first in a series of earthquakes to strike the coastal region of southern Sumatra, Indonesia. Another

Damage caused by the Peru earthquake to the church of San Luis, Cañete (Earthquake Engineering Research Institute/EERI Reconnaissance Team and Eduardo A. Fierro, team leader).

two major earthquakes (magnitudes between 7.0 and 7.9) struck the region soon after. The first occurred later the same day with a magnitude of 7.9 Mw and the second occurred the following day, 13 September, with a magnitude of 7.0 Mw. At least 25 people were killed, 161 others were injured and over 56,000 homes were destroyed or damaged in Bengkulu and West Sumatra, as a result of these earthquakes. They were felt strongly throughout the region as far away as Singapore, nearly 700 km from the epicentre. The magnitude 8.4 Mw event locates approximately 1,000 km southeast of the magnitude 9.3 Mw Sumatra earthquake in 2004.

On 1 April, an earthquake with a magnitude of 8.1 Mw occurred in the Solomon Islands triggering a destructive tsunami. The earthquake together with the associated tsunami caused the deaths of at least 52 people (with many others still reported missing), injured hundreds more and destroyed several villages in the area. Most of the casualties were reported to be from Gizo, where 500 homes were damaged and Sasamunga, where over 300 homes were damaged and a hospital was destroyed. Tsunami damage also occurred on Woodlark Island, Papua New Guinea where 17 houses were destroyed and a church was damaged. The earthquake was caused by the underthrusting of the Australia/Woodlark/ Solomon Sea plate beneath the Pacific plate, as part of the broader northeast directed subduction process. The Solomon Islands arc as a whole experiences a very high level of earthquake activity, and many earthquakes of magnitude 7.0 and above have been recorded in previous years.



Scientific Objectives

A Revised Seismic Hazard Map for UK

As part of the work involved with the introduction of the Eurocode 8 building regulations, overseen by a Committee of the British Standards Institute (BSI), new seismic hazard maps for the UK have been produced and published. These maps are issued in support of the UK National Annexe to Eurocode 8, to give guidance on the levels of peak ground acceleration (PGA) to be expected in different parts of the country.

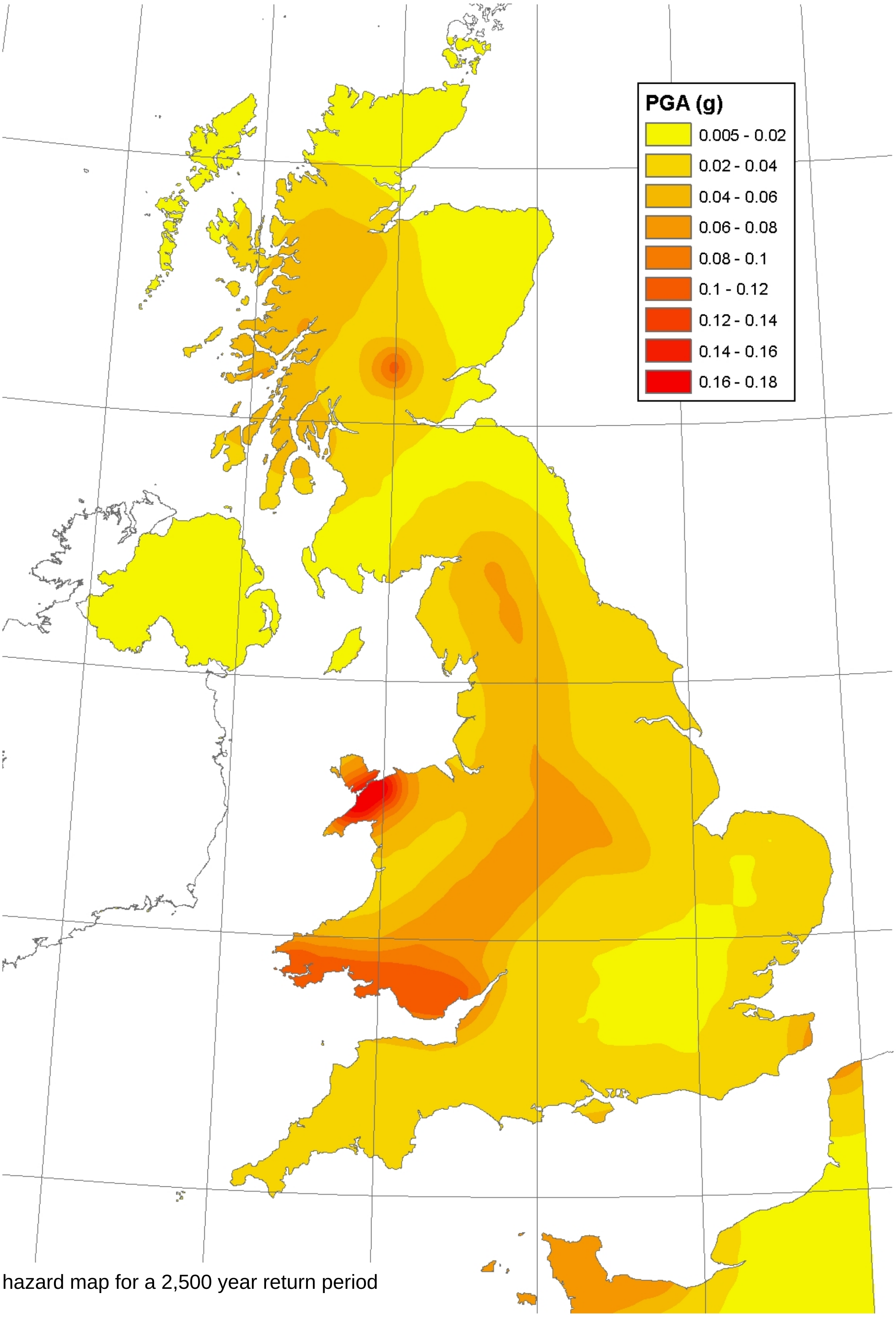
Two maps were constructed, with contours of PGA to be expected over return periods of 475 and 2,500 years. It was a requirement of the project that hazard should be depicted realistically rather than conservatively, and as a result, the maps show generally lower accelerations than previous studies – partly due to the fact that the calculations are based on a minimum magnitude of 4.5 Mw (about 4.9 M_L), excluding smaller events as not being of engineering significance even if they may produce short spikes of high acceleration.

The map shows that the part of the UK with the highest seismic hazard is Snowdonia, which has substantially higher PGAs than any other part of the UK. This is due to the regular occurrence of significant earthquakes in a concentrated area around Snowdonia and the Lleyn Peninsula throughout the historical record. The next most hazardous location is South Wales, which has also experienced notable earthquake activity over the last few hundred years.

The hazard was calculated using a seismic source model based on the seismotectonic model of the UK proposed by Chadwick et al. (1996), modified with respect to variations in the distribution of seismicity. The supporting material is published in a report by Musson and Sargeant (2007) which is freely downloadable from the web site of the Society for Earthquake and Civil Engineering Dynamics (www.seced.org.uk).

The Senior Seismic Hazard Analysis Committee (SSHAC) in the USA (Budnitz et al 1997) classify seismic hazard studies on a scale of 1 to 4 according to the extent that they address the full range of informed opinion in the hazard community. The most common level of study is level 1, where the study represents only the views of a single analyst or team of analysts. The study supporting Eurocode 8 in the UK is the first level 3 study in the UK. A panel of experts from the UK seismic hazard community made all major decisions about the model. Consequently, the model represents a consensus of informed opinion. PGA is calculated using the most recent and sophisticated empirical ground motion models, and a validation exercise confirmed that the seismicity modelling is realistic. These maps thus achieve a much higher degree of accountability than any previous comparable UK study.

This work was carried out by BGS with financial support from the Institution of Civil Engineers Research and Development Enabling Fund, ABS Consulting Ltd, and BSI.



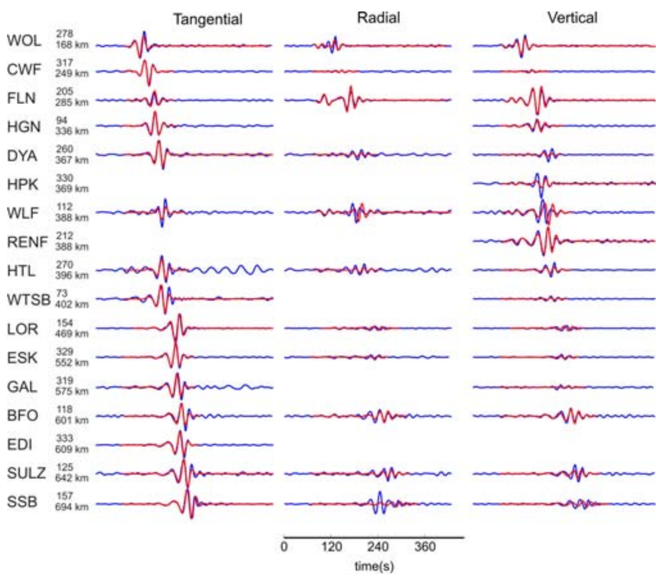
PGA hazard map for a 2,500 year return period

Scientific Objectives

Source Parameters for UK Earthquakes using Moment Tensor Inversion

The availability of high quality data from broadband stations in the UK and mainland Europe means reliable estimation of source parameters using moment tensor inversion can be successfully applied to recent British earthquakes. The method is particularly useful where sparse observations means that estimation of source parameters is not possible by other means.

A moment tensor is a mathematical representation of the seismic source based on force couples: combining force couples of different orientations can be used to represent a wide variety of seismic source types, including explosions. This turns out to be a good approximation for modelling the distant response of sources that are small with respect to the seismic wavelength. If we consider that the duration of the seismic source is short in time (seconds) and small in space (~100 km), the ground displacement recorded at a seismic station can be considered to be the linear combination of the moment tensor of the source and a function describing the effect of the path between the source and station. This path effect is called a Green's function and describes the displacement field at a given position in space and time due to a particular moment tensor component. Summing the individual Green's functions and moment tensor components gives the ground displacement at a given seismogram.



Observed (blue) and modelled (red) waveforms used in the moment tensor inversion of the Folkestone earthquake, 28 April 2007.

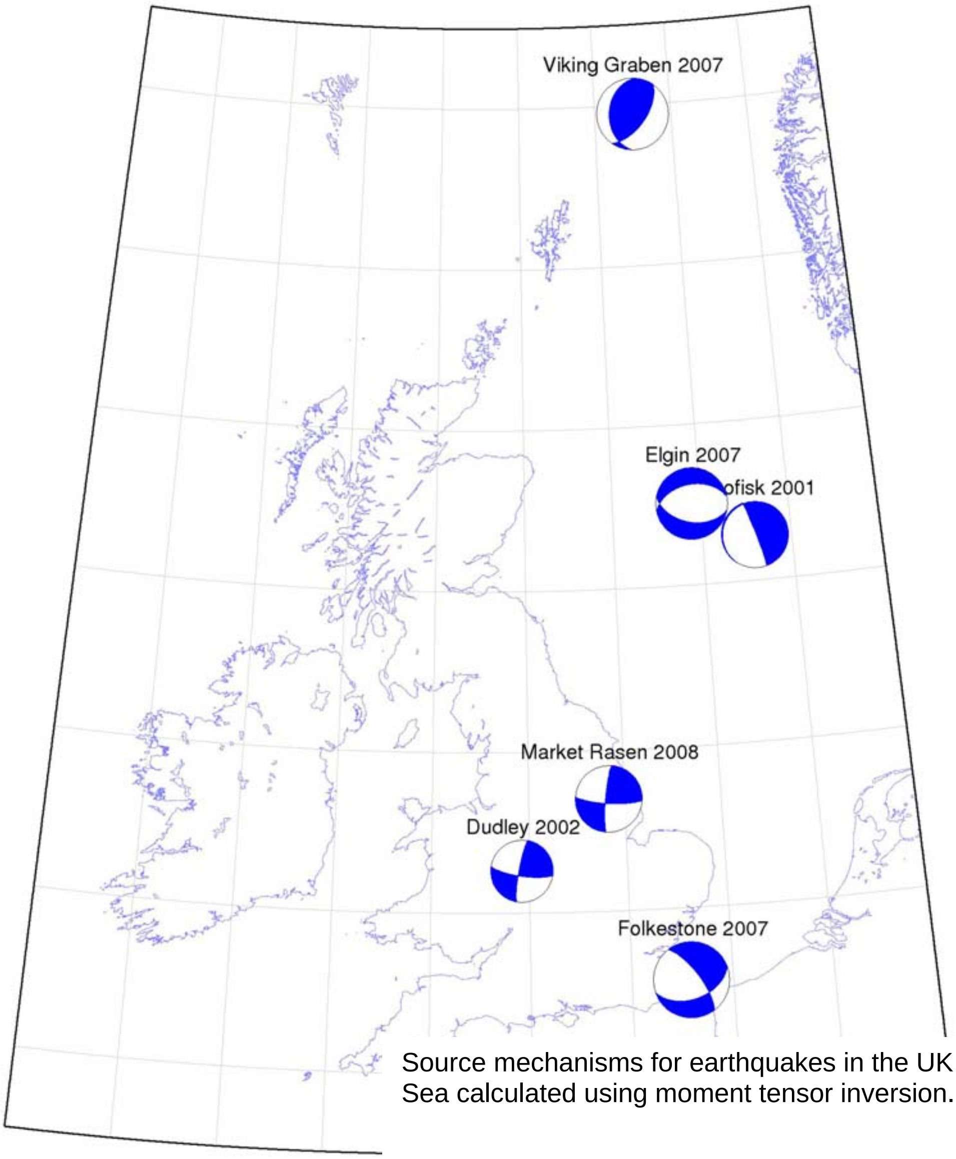
Given a model for the seismic properties of the Earth, Green's function for individual source-receiver pairs can be easily determined using a variety of well established methods, e.g. Muller (1985). These can then be combined with different moment tensors to find the one that best matches the observations. The linear relationship between the observed ground displacements and the moment tensor elements leads to a straightforward inverse problem to find the best-fitting moment tensor.

Analysis of smaller earthquakes (Mw ≤ 5.5) requires data recorded at regional distances (<3000 km) and uses the entire waveform rather than just a specific part. We use the method of Dreger (2003) to carry out the moment tensor inversion using long period observations recorded at regional distances across the UK and Europe. The moment tensor is determined through linear least squares inversion following Jost and Herrmann (1989) and decomposed into double couple and compensated linear vector dipole (CLVD) components.

Stations and components are manually selected based on the signal to noise ratio.

Synthetic waveforms are computed using a 1-D velocity model that does not account for lateral variations. This works as the waveforms are not very sensitive to the model at long periods. However, as the size of the earthquake decreases, short periods must be used, which means that the assumption of a 1-D velocity model may not be a good one.

The next stage of this work will be the application to previous moderate earthquakes in the UK. Application to smaller earthquakes will require modelling smaller wavelengths, where the assumption of a homogeneous 1D velocity model may no longer be a good one. We will investigate the use of 3-D velocity models for generating the Green's functions used in the inversion.



Source mechanisms for earthquakes in the UK and North Sea calculated using moment tensor inversion.

Scientific Objectives

Analysis of Variance

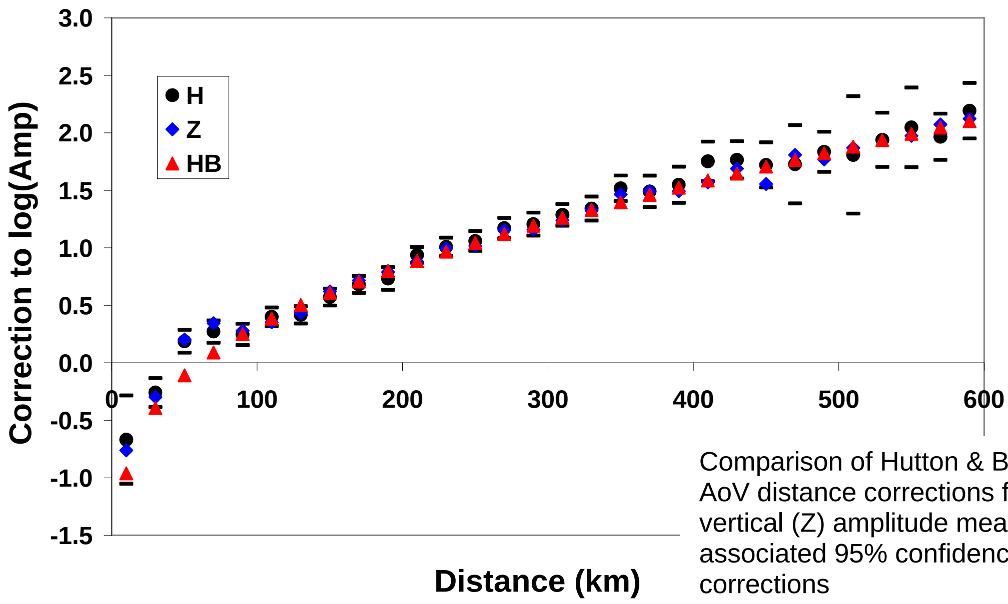
Seismic wave amplitudes and travel times vary with increasing distance from an earthquake, and the form of variation is regionally dependent. A statistical method applied to large datasets can evaluate these variations. They are used to determine local corrections for earthquake magnitude, and regional models of seismic velocity with depth.

BGS has compiled bulletins of data from UK earthquakes for many years, which contain hundreds of measurements of seismic wave amplitudes, and P- and S-wave arrival times. A statistical method, known as Analysis of Variance (AoV) has been applied to the data to extract useful information on the variation of recorded amplitude and travel time with distance, and also to determine amplitude corrections for local geology close to the BGS seismometer stations.

The recorded amplitude at a station can be partitioned into a source effect (the earthquake size), a distance effect (amplitude decreases with distance), and a station effect (relative amplification or attenuation due to local geology). We applied the AoV technique to 300 measurements of P-wave amplitudes from 40 earthquakes recorded at 25 stations (not all earthquakes are recorded at every station), and derived a table of amplitude corrections at a range of different distances from zero to 600km.

This can be used to obtain a new distance correction for local earthquake magnitude M_L, based on UK measurements.

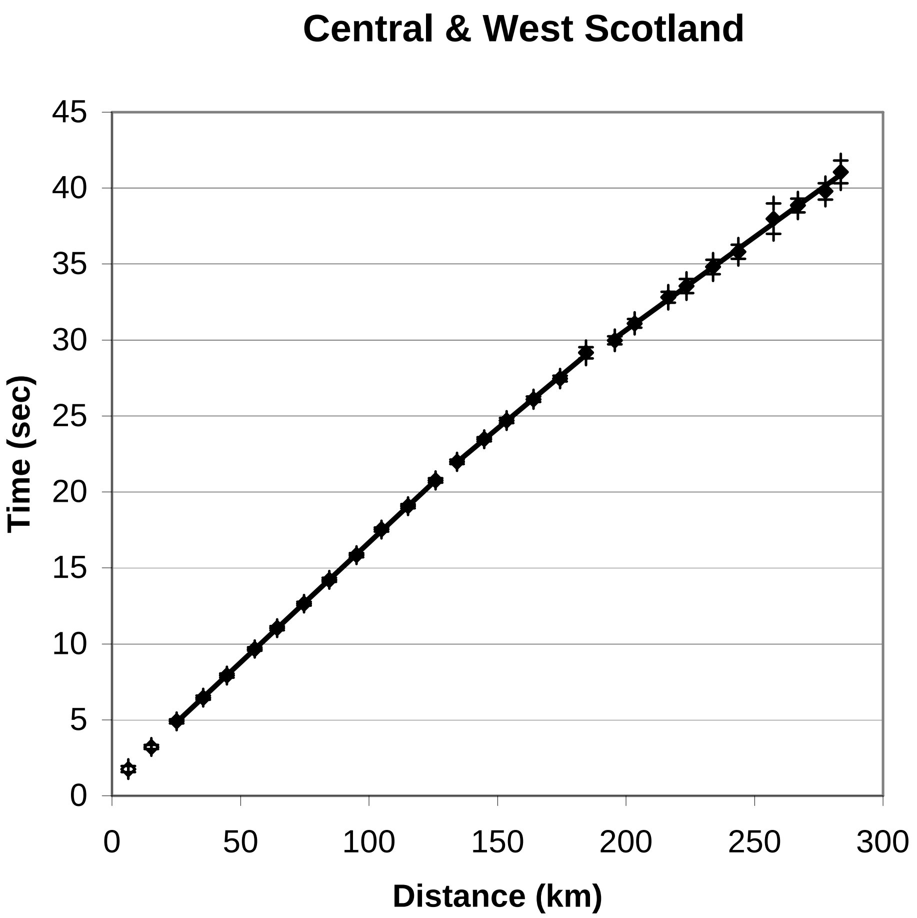
Comparison of the new distance correction



Comparison of Hutton & Boore (1987) and new AoV distance corrections for horizontal (H) and vertical (Z) amplitude measurements with associated 95% confidence error bars for H corrections with the Hutton and Boore (1987) correction customarily used for M_L calculation, based on observations in California, shows some differences in Lg wave propagation between California and the UK. However, over the range 90 to 400 km the corrections are very similar, implying that the crustal attenuation properties of Southern California and the UK are quite similar for S-waves and Lg waves at the observed wave frequencies: a relatively surprising result.

The AoV method also provides amplitude corrections for local geology close to the BGS seismometer stations. When used, these considerably reduce the variation in M_L as measured at different stations.

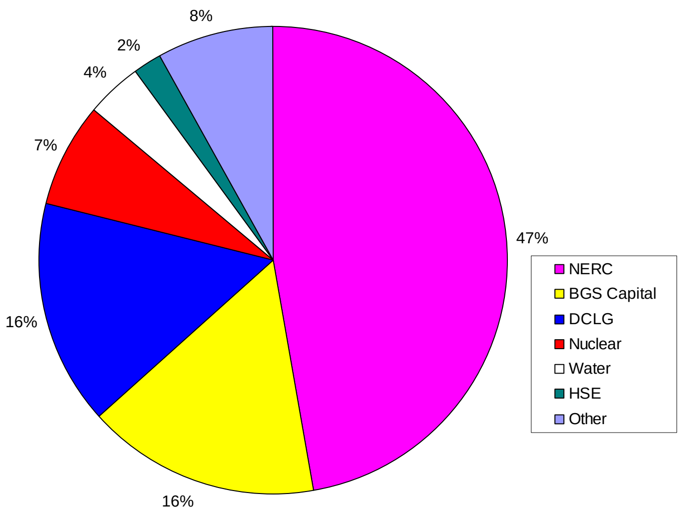
The variation of travel time with distance can be obtained in a similar way. Over 5000 observations of P-wave travel time to different stations in three different geographical areas were analysed using the AoV method, and the distance terms plotted. The travel time – distance plots can be sectioned into three or four approximately linear line segments, and these can be interpreted in terms of a 1D velocity depth model which can form a starting model for more sophisticated tomographic or inversion techniques.

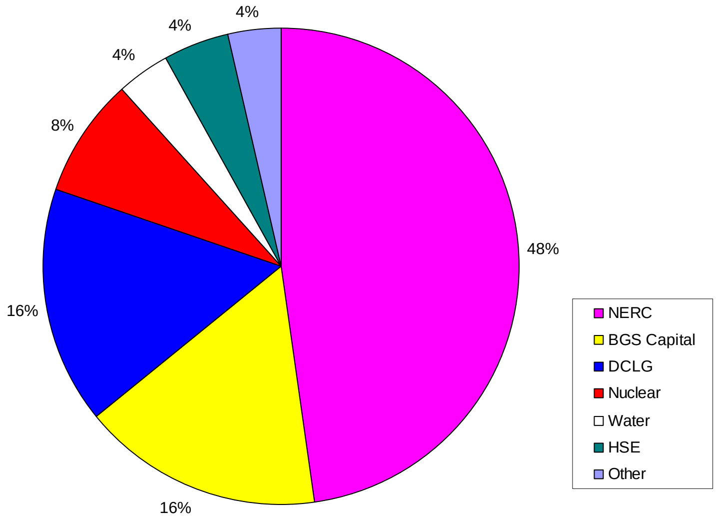


Distance terms obtained from AoV analysis of P-wave travel times for propagation paths in Central and West Scotland, showing 95% confidence limits (crosses) and observed linear trendlines.

Funding and Expenditure

In 2007-2008 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 2008-2009 remains approximately the same. There has been a slight decrease in the level of funding from NERC to £585 k. However, we have already secured a further £200k of BGS capital funds to continue with the upgrade of the monitoring network. 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
Aoife O'Mongain	Seismic Data Processing
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
Willie Velzian	Electronics Engineer
Computing Support	
Simon Flower	Senior Software Engineer
Dave Scott	Software Engineer
Consultant	
David Kerridge	Programme Leader

Appendix 2 Publications

BGS Internal Reports

Baptie, B. 2007. Earthquake Monitoring 2006/2007, BGS Seismic Monitoring and Information Service, Seventeenth Annual Report, BGS Internal Report IR/06/??.

Musson, R.M.W., Jiménez, M.J. and Gomez Capera, A.A., 2008. Macroseismic estimation of earthquake parameters, British Geological Survey Open Report, OR/08/004.

Musson, R.M.W. and Sargeant, S.L., 2007. Eurocode 8 seismic hazard zoning maps for the UK, British Geological Survey Technical Report, CR/07/125.

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Ottemöller, L and G. Ford, Earthquakes in the vicinity of the Elgin field in 2007. British Geological Survey, Commissioned Report, CR/07/153, 2007.

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In addition, six 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., 2007. Seismotectonics and state of stress in the British Isles, Abstracts of the 8th International Symposium on Upper Rhine Graben Evolution and Neotectonics.

Fernandez, M.G., Cecic, I. and Walker, A.B., 2007. European Seismological Commission: Past, Present, and Future. Proceedings of the IUGG XXIV General Assembly July 2007. ISBN 978-88-95852-25-4

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Appendix 3 Publication Summaries

Seismotectonics and state of stress in the British Isles

B. Baptie

The British Isles lie on the northwest European shelf and at the northeast margin of the North Atlantic Ocean. It's continental crust formed over a long period of time and has a complex tectonic history, which has produced much lateral and vertical heterogeneity through multiple episodes of deformation, resulting in widespread faulting. The underlying cause and distribution of earthquake activity in the British Isles is not clearly understood. Main et al. (1999) suggest that the observed neotectonic uplift combined with a direction of maximum (regional) stress deduced from earthquake focal mechanisms supports the theory that deformation is dominated by glacio-isostatic recovery. More recently, Bott and Bott (2004) and Arrowsmith et al. (2005) argue the earthquake activity is a response to an underlying hot, low-density anomaly in the upper mantle. Earthquake source mechanisms provide both fault geometries and principal stress directions that can be used to constrain our understanding of the driving forces of current deformation and to examine the nature and coupling of some of the competing ideas on seismicity and it's driving forces in the British Isles. However, unlike plate boundaries, where stress regimes are generally straightforward, intra-continental areas have often been subject to multiple episodes of deformation, the driving forces of deformation are less obvious. Furthermore, because of low seismicity rates, the number of reliable focal mechanisms is limited and previously published focal mechanisms for British earthquakes are relatively rare and are generally limited to the infrequent events of $M_L > 4.5$. To establish if these fault plane solutions can be explained by a single stress tensor orientation, i.e. homogeneous stress field, or if there are spatial variations in the stress tensor orientation British Isles, I invert the focal mechanism data to estimate a best-fitting stress tensor, under the assumption of uniform stress. Two different methods of stress tensor inversion are used, Gephart and Forsyth (1984) and Michael (1987), which each give different estimates of misfit. I examine spatial variations in stress tensor orientation by looking at the misfit of individual solutions from a number of best-fitting tensors. Spatial variations in misfit are then be used to examine the assumption of homogeneity.

Impact of a Lisbon-type tsunami on the U.K. 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 and S. L. Sargeant

[1] We investigate the propagation of tsunamis toward 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 U.K. coastline. Because of 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 reamplification 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 comparison of the seismicity of the UK and southeastern Australia

K.F. McCue, R.M.W. Musson, and G. Gibson

In principle, the Global Seismic Hazard Assessment Program enabled, for the first time, the seismic hazard in areas of like tectonic setting to be compared. In practice, the formal process was not rigorously applied in some areas including Australia and the UK. We use modern and historical data, and strong motion information (intensity) to compare the seismicity of the UK where there is a 1000 yr long written history with a similar sized area in southeastern Australia with a 150 yr written history. These data are used to comment on the association of earthquakes and geological structure, to produce risk estimates for strategic areas within each of the two regions and to discuss the differences in engineering code requirements. If likeminded societies have a different response to risk assessment then the question why needs to be asked.

Folkestone earthquake 28 April 2007

R.M.W. Musson and A.B. Walker

On 28 April 2007, a magnitude 4.0 Mw earthquake struck Kent, the south-easternmost county of England. Such small earthquakes are common worldwide, and even in the UK can be expected with a recurrence interval of around 5.7 years (Musson 2007). However, this earthquake was exceptional. Owing to a combination of an epicentral location close to a town, a shallow focal depth, and perhaps also unfavourable site conditions, significant damage was caused in the town of Folkestone, an important ferry port in the English Home Counties, situated between a nuclear power station to the west and the Channel Tunnel to the east. One person was injured, and it was good fortune and good timing (the event took place early on a Saturday morning) that no-one was killed. The damage in parts of Folkestone was so severe that many houses had to be evacuated, and this earthquake is the first on record for which a UK local authority has needed to implement emergency procedures. It serves as an indication that, in low seismicity areas, even small earthquakes can have societal consequences, and the earthquake is thus of rather more interest than its low magnitude would imply.

Macroseismic effects of the 2007 Cape St Vincent earthquake from the EMSC online questionnaire

R.M.W. Musson

It is a principle of the EMS-98 intensity scale, and the MSK scale before it, that intensity should be assigned to a community rather than an individual observation. Thus, when it comes to the question of automatic intensity assessment from data gathered online, the ideal way to proceed must be based on finding a way to compare a collection of reports from a single place, to the idealised descriptions provided by the scale. Such a system, under development by BGS Edinburgh, initially for use with UK data, is now being tested in Europe in collaboration with EMSC. The recent earthquake of 12 February 2007 (6.1 Mw) with epicentre off Cape St Vincent, Portugal provided the first real test. This earthquake was widely felt in the Iberian Peninsula (as far as Madrid), and a total of 183 questionnaires were collected from the EMSC web site. These reports reduced to 79 places when sorted by grid square. Of these, only seven squares yielded five or more reports. The remainder could only be categorised as “felt” or, in one case, “not felt”. The largest number of observations, not surprisingly, came from Lisbon (32 reports, intensity 5). Of the seven locations for which intensity was assigned, five were 5 EMS, with one 4 and one 3 EMS. A location west of Huelva, Andalucía, almost reached intensity 6 on the basis of eleven reports. Of these, two reported minor damage, and all reported large and small objects being thrown down.

The 2007 UK national seismic hazard map

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

Since the UK is a country of only low to moderate seismicity, in the past not much importance has been placed on national maps of seismic hazard. Although a map of sorts was published as long ago as 1976 for Great Britain, it was not until the mid 1990s that probabilistic seismic hazard maps were officially commissioned for the land area of the UK; these were published in 1997. In the years since then, although the UK was, of course, included in the maps resulting from the GSHAP and SESAME projects, the only update within the UK was the publication of a single EMS intensity hazard map in the BGS Atlas “Britain beneath our feet”. However, the introduction of Eurocode 8 requires the production of a National Annexe covering the intended application of Eurocode 8 to the UK. This in turn requires an updated hazard map that can be used as the basis for seismic zoning. Accordingly, a new hazard map for the UK, giving PGA values with a 90% probability of not being exceeded in 50 years, has been prepared by BGS with financial support from the Institute of Civil Engineers Research Support Fund, ABS Consulting, and the British Standards Institute. The source zone model is an update on the model used in 2004 for the BGS Atlas, incorporating a greater reliance on seismotectonics viewed as a kinematic process. This project also marks the first use of NGA (Next Generation Attenuation) ground motion models in the UK. The results confirm what might be expected, that the whole of the UK is a low-hazard area.

Next Generation Attenuation (NGA) and other recent ground motion models applied to the UK

R.M.W. Musson

The occasion of the production of a new national seismic hazard map for the UK (in connection with the UK National Annexe to Eurocode 8) provides an impetus to reflect on the perennial problem of the selection of strong ground motion models for use in the UK in the absence of sufficient local data for the construction of a UK-specific model. Recent investigations of ground motion data from the UK and NW Europe suggest that such data as exist do not match predicted values from well-used ground motion models commonly adopted. An objection made against the use of such local data from small (<5.5 Mw) earthquakes is that what are essentially weak ground motions cannot be used to scale up to strong ground motions. However, this implies the converse, that models based on strong ground motion form large earthquakes cannot be scaled down to model the sort of smaller events that dominate the hazard in areas of low to moderate seismicity. A hybrid weak-strong model was considered but rejected on the grounds that the weak motion part of the model was still insufficiently well constrained. An attractive solution appears to be the adoption of models from the Next Generation Attenuation (NGA) project. These models, although intended for use in active areas, employ much more advanced scaling procedures than have been used hitherto in strong ground motion modelling, which suggests that these models should be more capable of dealing accurately with situations where the hazard is predominantly from earthquakes in the range 4.0-5.5 Mw. The results are compared to those that would be obtained from some models previously used in the UK, and some other models recently developed in Europe.

A little historical information changes the tectonic interpretation: the mystery of the Western Makran

R.M.W. Musson

The Makran subduction zone, which runs along the south-eastern coast of Iran and the southern coast of Pakistan, is a source of great earthquakes and a major control on the seismic hazard of the region. There is a problem, however, in interpreting the apparent aseismicity of the Western Makran. It could indicate a zone locked throughout historical times, or it could be that subduction is occurring aseismically or even not at all. Evidence for seismic activity rests on one event, apparently very large, in 1483, which supposedly caused damage from the Straits of Hormuz to Southern Oman. Historical research, especially taking into consideration the political situation in the region at the end of the 15th century, suggests that this 1483 event was a moderate magnitude earthquake in the vicinity of Qeshm Island that has been misassociated with a second, very badly documented, earthquake that occurred fourteen years later. This new interpretation removes from the earthquake catalogue any evidence for earthquake activity along the Western Makran, and adds weight to a new tectonic interpretation that suggests that the active Makran subduction zone is controlled by the Murray Ridge spreading centre, and has a westerly termination at the Sonne Fault. This presents an interesting (even extreme) example of how a piece of obscure historical information concerning political links has a major effect on resolving a question of tectonic interpretation, and with it, strongly influences the estimation of regional seismic hazard.

Eurocode 8 seismic hazard zoning maps for the UK

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

This report provides national seismic hazard maps compiled by the BGS for the purposes of seismic zoning within the Eurocode 8 context. It was commissioned to assist the drafting of the UK National Annexes to the structural Eurocode BS EN1998: Design of structures for earthquake resistance (EC8). The hazard maps this study produced are contained in the British Standards Institution Published Document PD6698:2007: Background paper to the UK National Annexes to BS EN 1998-1, 1998-4, 1998-5 and 1998-6. The use of values on the maps as design coefficients, replacing site-specific studies, is not generally considered best practice. The values are intended to give a general indication of the expected hazard level. Two maps are provided, with return periods of 475 years and 2,500 years, both showing horizontal peak ground acceleration (PGA) for rock site conditions. PGA is here defined as the geometric mean of the two horizontal components (and not the larger component as was frequently the case in previous studies). Values were computed over an area bounded by 49 - 59o N and 8o W - 2o E. The computations were made for points distributed on a grid at approximately 15 km intervals in both directions, and this defines the spatial resolution of the maps. Key decisions respecting the modelling decisions for the study were taken by a panel of experts convened at the Institute of Civil Engineers (ICE) on 26 April 2007; thus the model takes into account, to a large degree, a consensus of opinion of the informed seismic hazard community in the UK.

British earthquakes

R.M.W. Musson

Although the UK is not a strongly seismic region, the study of earthquakes in Britain presents many interesting points. Firstly, British earthquakes are rather well documented through history, partly due to the intellectual development and literacy of the country, and partly because British earthquakes have always been so newsworthy that even minor events have been recorded in some detail. Secondly, as is rather typical for intraplate areas, the relationship between seismicity and geological structure is unclear. The definitely non-random spatial pattern of British earthquakes is clearly due to something, but among competing theories as to what that something is, no hypothesis is clearly the best. In this paper the subject of British seismicity is viewed from several angles. First, the sources that underlie the earthquake catalogue are discussed in order to give a clear indication of the limits on the completeness and accuracy of the data. General statistics for earthquake occurrence in the UK are then presented. This is followed by a description of British seismicity from region to region, with remarks on some key earthquakes of interest. Different hypotheses on the nature of the tectonic or geological control are then reviewed and assessed. Finally, the subject of active faults in the UK is discussed, from the point of view of general seismic hazard assessment.

Macroseismic estimation of earthquake parameters

R.M.W. Musson, M.J. Jiménez, and A.A. Gomez Capera

The derivation of earthquake parameters from macroseismic (intensity) data is an inveterate problem. Yet for earthquakes in the pre-instrumental period (roughly, before 1900) intensity data points (IDPs) are the only form of numerical data available to the seismologist. In order to produce a numerate, consistent catalogue of historical earthquakes that can be combined in a compatible way with modern instrumental data requires some system for estimating what instrumental parameters would have been obtained had seismometers been in operation. A major aim of the NA-4 module of the European Framework project NERIES is to produce a catalogue of European earthquakes before 1900 in which there is the greatest possible level of internal consistency in the determination of earthquake parameters. This means the use of uniform procedures for determining earthquake parameters over the whole of Europe. Finding suitable procedures that can be used for this is a difficult task. The parameters to be determined are essentially the location and the size of each earthquake. Precisely how one defines location in this context is arguable – one speaks of the “macroseismic epicentre”, but this is not necessarily exactly the same as an epicentre in the sense of the surface projection of the point where an earthquake rupture initiates. “Size” has to be considered here to mean “magnitude”; whereas many earlier historical earthquake catalogues were content to use epicentral intensity, Io, as a size measure, for modern applications, and for consistency with modern data sets, this is not enough, and magnitude, preferably moment magnitude, Mw, has to be estimated. This report is organised in the following way: some of the technical issues involved are described in a general way in Section 2. Section 3 provides a review of previous methods and studies. Then Section 4 outlines the methods that are proposed and recommended for the NERIES project.

Earthquake parameter estimation from historical macroseismic data

R.M.W. Musson, M.J. Jiménez, and A.A. Gomez Capera

As part of the NERIES (Network of Research Infrastructures for European Seismology) project, a catalogue of the larger European earthquakes from 1000-1900 is being newly compiled. A problem with previous pan-European catalogues is that they all involve merging of national catalogues that were compiled in different ways, leading to inconsistencies in the final result. A fundamental goal of the NERIES catalogue is that all events should be assessed using the same homogeneous procedures from the basic raw material, i.e. the intensity data points (IDP). Defining suitable procedures is, however, far from straightforward. A number of competing methods have been proposed in the past, and the issue of calibration is problematic. After extensive surveys of current practices, a test was conducted in which some modern IDP sets were massaged to resemble historical data sets. Results suggest that methods relying on a grid-search, attenuation-fitting approach perform better than other methods. We propose here a method based on the mechanics of earthquake perception, which allows for parameter estimation in different parts of Europe without the need for separate calibration exercises. An initial epicentral estimation is made on the distribution of high intensities. This is used as the starting point for fitting an intensity attenuation model, which gives the final solution of both epicentre and depth. Finally, the data set is compared to expected intensity distributions from different magnitude events to provide the estimated magnitude, Mi, equivalent to Mw.

A comparison of EMS and MMI macroseismic intensity assignments from online questionnaires

S. Gilles, R.M.W. Musson, R. Bossu, D.J. Wald, and V. Quitoriano

The purpose of this work is to compare the results of macroseismic studies when using two different macroseismic scales (namely, MMI and EMS98) and different Internet-based intensity assignment methods. The study is based on online questionnaires collected at the Euro-Med Seismological Centre (EMSC); this questionnaire, available in 19 languages, is based on the British Geological Survey (BGS) questionnaire and is complemented with all the other questions from the U.S. Geological Survey (USGS) form (known as “Did you Feel it”). The EMS assignment method mimics human reasoning in arriving at intensity assessment, in contrast to the US approach, which is based on mathematical regression formulae to reach decimal values of MMI. Both approaches are applied to the same sets of EMSC macroseismic questionnaires to identify possible differences between the assignment methods. A comparison with MMI intensities from USGS questionnaires is also performed.

Earthquake in Lincolnshire, 27 February 2008

R.M.W. Musson

The Market Rasen earthquake of 27 February 2008 (5.2 M_L) was the largest British earthquake since 1984, and the largest in England since the 1957 East Midlands earthquake. Fortunately, due to the considerable focal depth of the event (about 20 km) there was no severe damage anywhere; in contrast, for instance, to the 1185 Lincoln earthquake which partly destroyed Lincoln cathedral and threw down many houses. This article describes the response by BGS to the earthquake as it developed during the day, following the earthquake’s occurrence at approximately 1 a.m., and places it in the context of seismology in the UK.

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

L. Ottemöller 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.

Development of seismic methods to automatically identify tsunamigenic events and generate alerts: Phase 1 Operational developments.

L. Ottemöller and R. Luckett,

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 1 of the project: ‘Operational developments’. The objective of this work is to establish a system that detects earthquakes in the area of interest that could become part of a larger integrated tsunami warning system, if that was to be implemented in the future.

The basic components of an earthquake detection system are software and hardware that process data from seismic stations. We have selected and implemented the EarlyBird software developed at the US West Coast and Alaska Tsunami Warning Center that has all the functionality required to detect earthquakes for tsunami warning. The software is well established and has been in operation at tsunami warning centres for a considerable time. We have selected more than 100 seismic stations and established the data flow to provide good coverage for our monitoring area, 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. Earthquakes in this area with magnitude greater than 5 are detected within minutes, magnitudes are determined and automatic alerts issued. The system has been in operated reliably for over six months and has detected earthquakes in most areas with potentially tsunamigenic sources that could affect the UK. The detection level is lower than required, considering that tsunami generation generally requires magnitude 6.5, which gives confidence that large earthquakes will be detected successsfully.

Seismic detection is only one component of tsunami warning. However, occurrence of an earthquake is the first indication that tsunami may be generated. A complete tsunami warning system has to incorporate real-time tide gauge and possibly deep sea pressure data (as being investigated by POL in a parallel project). Just as important for successful tsunami hazard mitigation are education and the dissemination of information. The Northeast Atlantic and Mediterranean have been identified by the Intergovernmental Oceanographic Commission (IOC) of UNESCO as areas for which tsunami warning systems should be established. The implementation plan for this proposes the setup of a preliminary system by 2007 and the final system by 2011. However, priority has been given to the Mediterranean area so far.

Explosions in the BGS Seismic Database in the Area of Beaufort’s Dyke, 1992-2007.

L. Ottemöller and G. Ford

Beaufort’s Dyke in the North Channel, and surrounding waters were used as a munitions disposal site during the 20th Century, with significant quantities after the two world wars and the last dumping in 1976. The British Geological Survey (BGS) over the years has detected explosions in this area on their seismograph network. Significant explosions were located and kept in the database. The BGS seismicity database also contained smaller explosions that possibly originated in this area between 2005 and 2007, but had not undergone analysis and were thus not given a location. This report describes work carried out to complete the catalogue of underwater explosions in the Beaufort’s Dyke area. Using detection on the nearby seismograph networks as the search criterion, a total of 476 explosions were considered in this study. Two of these were identified and located in the Beaufort’s Dyke area, increasing the total of explosions in this area recorded in the BGS database to 49. However, it is almost certain that the list of explosions is not complete, since due to previous routine practice, records of smaller explosions were discarded or not detected. In future, it will be possible to improve completeness by analysis of all events in this area based on the existing stations. Installation of additional seismograph stations would help to detect smaller explosions.