British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Earthquake Monitoring 2006/2007

BGS Seismic Monitoring and Information Service

Eighteenth Annual Report

BRITISH GEOLOGICAL SURVEY

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UK Earthquake Monitoring 2006/2007

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Summary

The British Geological Survey (BGS) operates a network of seismometers throughout the UK to reliably detect seismic events 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 18th year of the project five new broadband seismograph stations were established, giving a total of fourteen broadband stations. Real-time data from all broadband stations are 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 are also incorporated into our automatic data processing systems 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 eighteen broadband sensors and high dynamic range digitisers.

All significant events were reported rapidly to the Customer Group through seismic alerts sent by e-mail. The alerts were also published on the Internet (http://www.earthquakes.bgs.ac.uk). Monthly seismic bulletins were issued six weeks in arrears and compiled in a finalized annual bulletin (Simpson, 2007). In all reporting areas, scheduled targets have been met or surpassed.

Seven papers have been published in peer-reviewed journals and three presentations were made at international conferences. Ten BGS internal reports were prepared along with two confidential reports. Two new PhD studentships, partially funded by the project, started in October 2006 at Cambridge and Edinburgh.

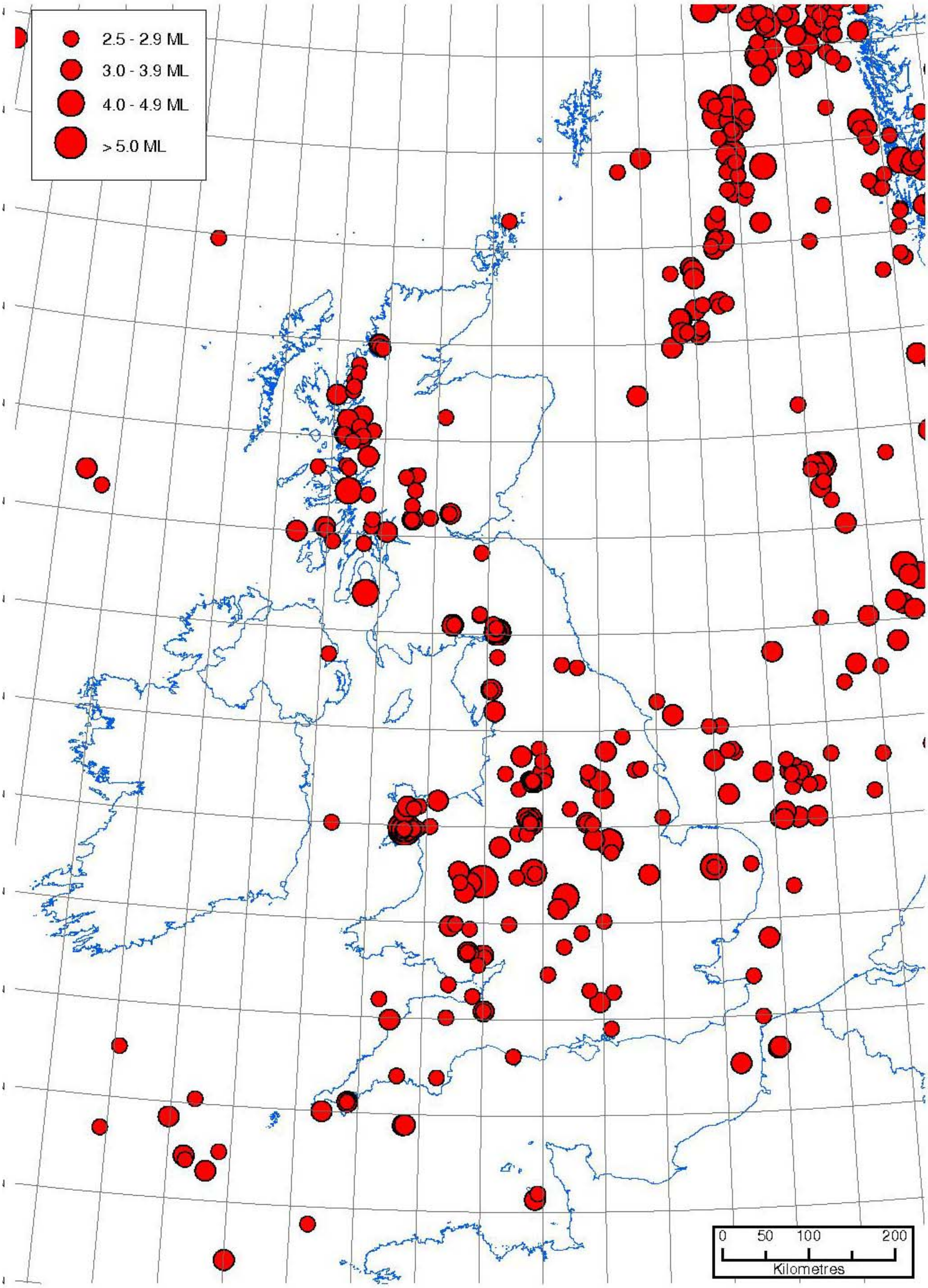
Introduction

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 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 Seismic Monitoring and Information Service aims to rapidly identify the sources of seismic events, which are felt or heard.

In an average year, about 200 earthquakes are detected and located by BGS, and around 15% are felt by people. Historically, the largest known British earthquake occurred on the Dogger Bank in 1931, with a magnitude of 6.1. 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 onshore UK earthquake known was in the Colchester area (1884) with the modest magnitude of 4.6 *ML*. 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 risk 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 2006

Monitoring Network

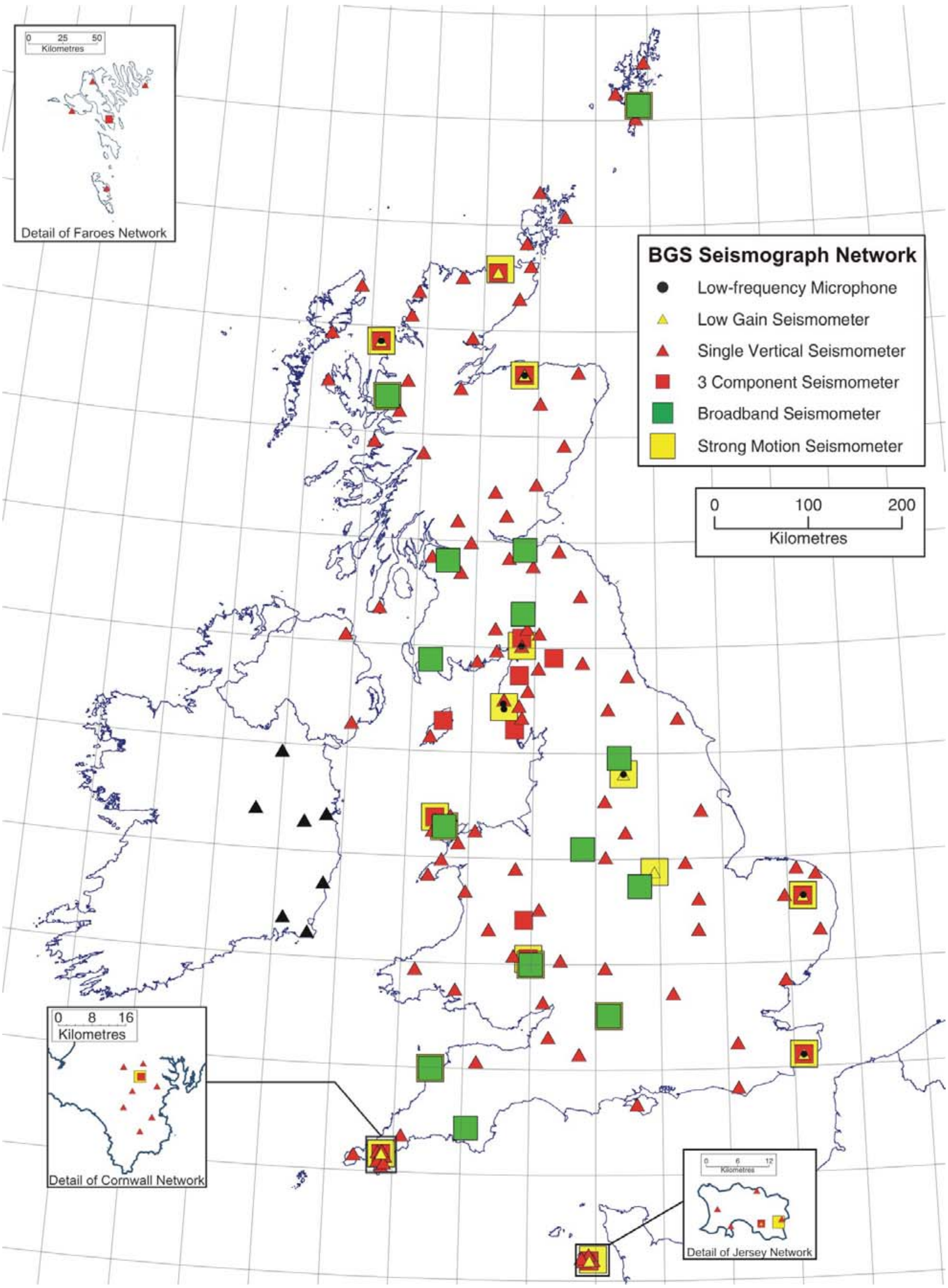
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. Over time, the network has grown to 146 stations, with an average spacing of 70 km, giving UK-wide coverage and a detection threshold of 2.5 ML for all onshore earthquakes, even in poor noise conditions.

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 is 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 modem to transfer all automatically detected events to the BGS offices in Edinburgh. Once transferred, the events are analysed to determine 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 fourteen broadband sensors at stations across the UK.



BGS seismograph stations, March 2007

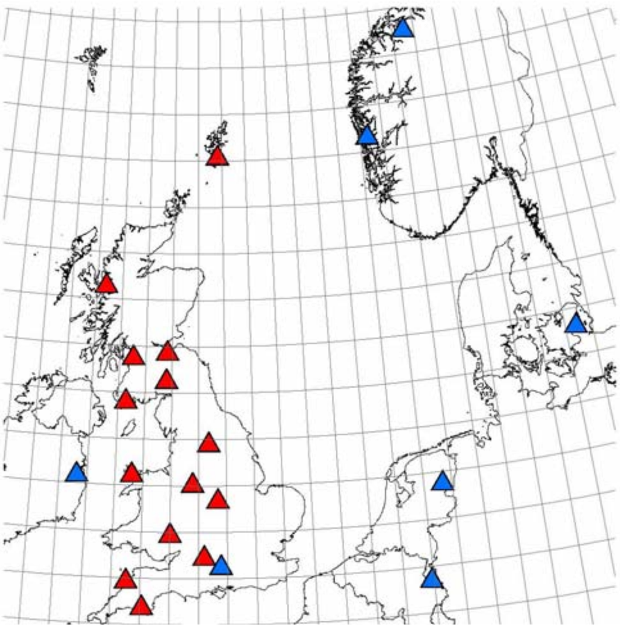
Achievements

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 potentially tsunamigenic seismic events in the North Atlantic.

In the last year new broadband stations were installed at: Galloway (Dumfries and Galloway), Haverah Park (Yorkshire), Yadsworthy (Devon), Llynfaes (Anglesey) and Newchapel (Stoke-on-Trent). Continuous data from all five stations are transmitted in real-time to Edinburgh, where they are used for analysis and archived.

We have also carried out site surveys for possible broadband deployments in Cornwall and Keswick (Cumbria).



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

Signals from the broadband seismometers are recorded using high dynamic range data acquisition so that data remains on-scale for a wide range of signals.

Communications at our broadband station at Charnwood Forest, Leicestershire, have been upgraded by installation of a broadband satellite link. This means that continuous data from this site is received in near real-time at Edinburgh. Telephone links to all network base stations except Minch (Northwest Scotland) and the Scottish Borders have all been upgraded to use high-speed ADSL connections.

Although all fourteen of our broadband stations transmit data in real-time, a ring-buffer of data is also held locally at the recording site, in case of any communications failures. This ensures that data is not lost, even for lengthy outages.

Eighteen new broadband seismometers were purchased during the year 2006-2007. These will be deployed either at existing or new stations as part of our network development program. We will also maintain a pool of broadband sensors that can be rapidly deployed for studying aftershock sequences, earthquake swarms and specific studies.

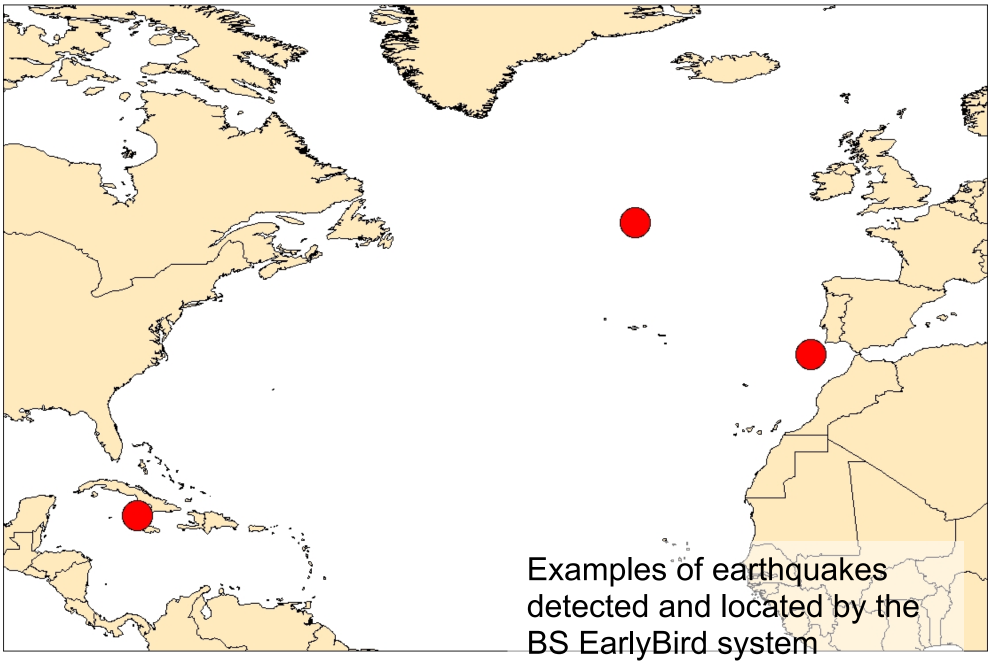
Near real-time data from short period stations in our Hartland, Keyworth, Kyle, Lownet, Shetland and South East England seismic networks are now being transferred directly to Edinburgh, where they are incorporated into automatic detection and location schemes. Our aim is for all data from remote outstations to be transferred directly to Edinburgh, to improve our response to any seismic events.

Data from other seismic stations operated by European partner agencies have also been incorporated into our near real-time processing. These include data from Denmark, 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.

Previous studies commissioned by Defra have shown that there is a small but non-negligible risk to the UK coast from tsunami originating in the north-eastern Atlantic region. As a result, Defra have asked BGS to carry out further work to examine the possibility of seismic detection of tsunamigenic events and the generation of automated alerts. The aim is to strengthen the national capability to detect earthquakes that could generate tsunami affecting the UK. The systems developed could become part of a UK or regional tsunami warning system.

The first task of a tsunami warning system is the detection of earthquakes and evaluation of their potential to generate a tsunami, based on data from seismic stations. We have identified seismic stations bordering the Atlantic able to provide such data, contacted the operating agencies, and secured agreement to access and integrate their data with data from the UK. Data processing must be carried out in near real-time, defined as a data latency of less than about 2 minutes. To do this we have implemented the *EarlyBird* software, used by the US West Coast and Alaska, Pacific and the Caribbean Tsunami Warning Centres. The system has been under test since the end of 2006 and has successfully automatically detected a number of events, including a magnitude 6.0 M_w earthquake at the Azores-Gibraltar Fault Zone that is believed to be located close to the epicentre of the catastrophic 1755 earthquake that destroyed Lisbon and also generated a devastating tsunami.



Examples of earthquakes detected and located by the BS EarlyBird system

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 receive seismic alerts by e-mail whenever an event is felt or heard by more than two individuals. Major global earthquakes are also reported.

Alerts were issued for 18 UK events within the reporting period. Six of these were suspected to be of a sonic origin and one was for an explosion in Liverpool Bay. Eight distant earthquakes were also reported. In all but one case (Liverpool Bay) the alerts were issued to Customer Group members within two hours of a member of the 24-hour on-call team being notified. The alerts include earthquake parameters, reports from members of the public, damage and background information. In addition, three enquiries were received from Nuclear Power Stations after alarms triggered, and a response was given within 15 minutes in all 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. This was used to collate and process macroseismic data following the Dumfries earthquake. At this time we still need to produce the maps manually, but our aim is to be able to produce fully automatic macroseismic maps for the Seismology web pages that will be updated in near real-time as data is contributed.

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 2006, it was issued within five months.

Achievements

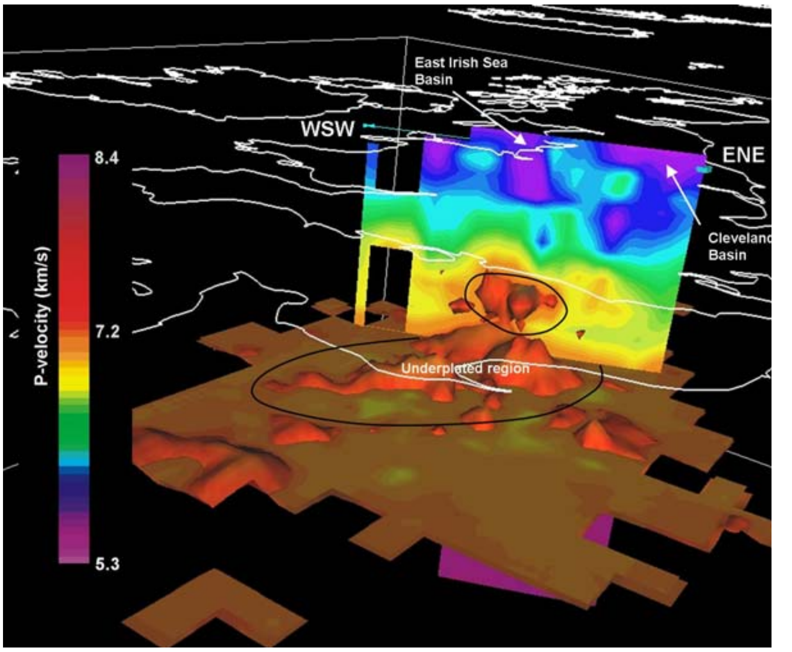
Collaboration and Data Exchange

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 the University of Leicester has developed a 3-D tomographic model of seismic P- wave velocity (V_p) and the P- to S-wave velocity ratio (V_p/V_s) beneath England and Wales using arrival time data from local earthquakes recorded by stations in the British Geological Survey (BGS) seismic monitoring network. 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 appears to be intrusive, has been 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.



Depth profile WSW-ENE through the underplated region. Isosurfaces showing regions with a P-velocity in excess of 7.2 km/s are contoured. A secondary body above the thickest region of underplating directly underlies the East Irish Sea Basin.

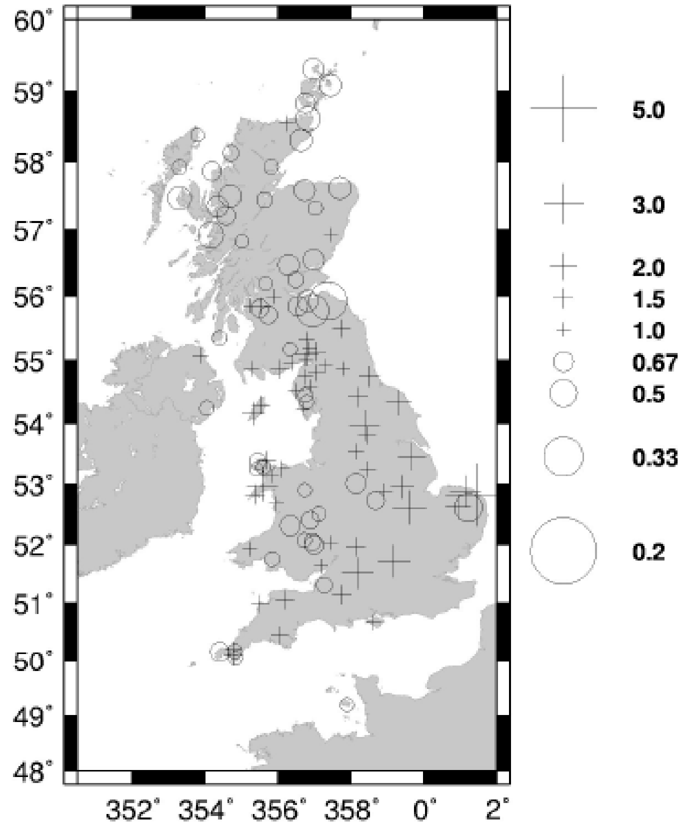
A BGS CASE student at the University of Liverpool is studying source, path and site effects by inversion of earthquake data from the BGS catalogue. Over 2500 records from 226 events (2.0 > ML > 4.7) from the year 1992 until present have been used in the inversion scheme to determine the quality factor *Q*, seismic moments and stress drops.

The results suggest a frequency-independent, depth-dependent Q structure. A linear relationship proportional to 0.62ML between moment magnitude (Mw) and local magnitude (ML) is found in the range of 2 to 4.7 ML. Most stress drops are found to be between 1 and 10 bars, 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, with amplification occurring in the Cenozoic sedimentary rock sites in the south east of England and deamplification occurring in the harder Palaeozoic rock sites of Wales and Scotland.

A PhD student at Edinburgh University, funded partially by BGS, is using ambient seismic noise records to construct Green's functions for seismic surface waves between station pairs. This project started in October 2006 and will use data recorded on broadband seismometers across the UK to construct maps of surface wave group velocity at different periods, that can be interpreted in terms of 3-D variation in the structure of the crust and upper mantle. Initial results using a limited test data set reveal stable arrivals that broadly match the expected propagation characteristics.

A new BGS CASE student at the University of Cambridge will use 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 will be collected from permanent BGS broadband stations and temporary deployments 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.



The spatial distribution of station amplitude correction factors determined by inversion for attenuation parameters. Circles indicate de-amplification, crosses indicate amplification.

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 and also on monitoring seismicity in the North Sea.

KNMI (Netherlands) and BGS have worked together on the Buncefield explosion.

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. 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 ORFEUS, the regional data centre for broadband data, in near real-time.

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.

In 2006-2007 BGS received a learning award from the National Endowment for Science, Technology and the Arts (NESTA) to set up a project entitled “School Seismology in the UK”. This award was supplemented with funding from BGS. The first aim of the project was to develop specific resources for teaching and learning seismology in UK schools. These resources are being distributed free of charge to teachers in the UK in the form of a booklet of classroom activities published by the Science Enhancement Programme (SEP) associates scheme. 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 is 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 will 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.

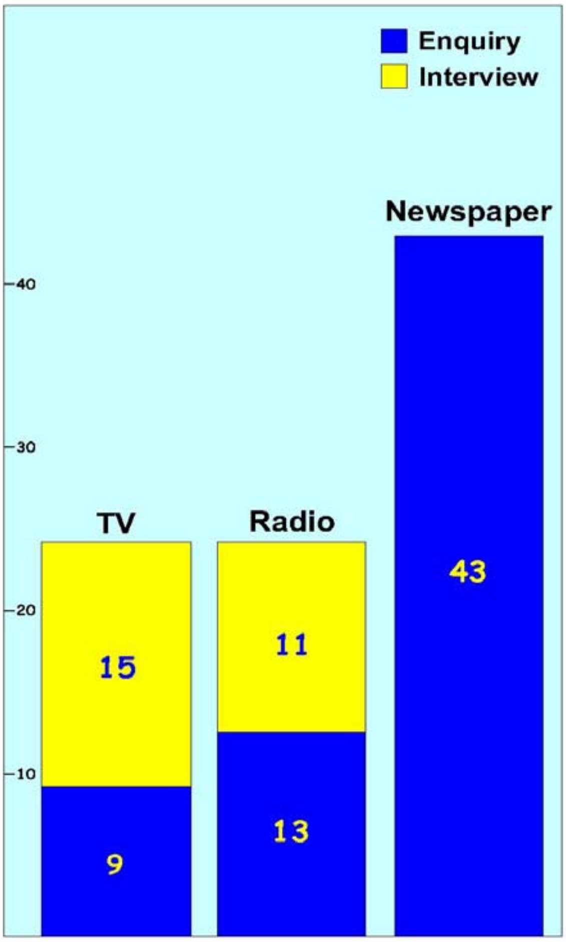
A seismometer has been developed by SEP and has been tested alongside BGS instrumentation. The final version, produced by MUTR, will be available for distribution to schools in 2007-2008. BGS will fund the next phase of the project into 2007-2008, providing support for the distribution of these seismometers to interested schools. BGS will also develop an online database that will enable schools across the UK to exchange data.

The SEP “School” seismometer

A number of lectures and presentations were given to schools, university students and other interested parties. The BGS Open Day in September attracted 960 visitors with many of them visiting the interactive earthquake display. A further 158 school pupils from nine different schools visited during the following Schools Week.

The Seismology web site continues to be widely accessed, with over 285,000 visitors logged in the year. A significant peak was observed in December, following the Dumfries earthquake, when over 4,800 visits were recorded on 26 December.

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 2006-2007, 542 enquiries were answered. Some 91 of these were from the media, including 48 for TV and radio broadcasts following significant earthquakes. The broadcasting enquiries led to 15 TV and 11 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 2006, published and distributed in May 2007 (Simpson, 2007).

There were 64 earthquakes located by the monitoring network during the year, with 15 having magnitudes of 2.0 ML or greater and four having magnitudes of 3.0 ML or greater. Three events with a magnitude of 2.0 ML or greater were reported felt, together with a further four smaller ones, bringing the total to seven felt earthquakes in 2006.

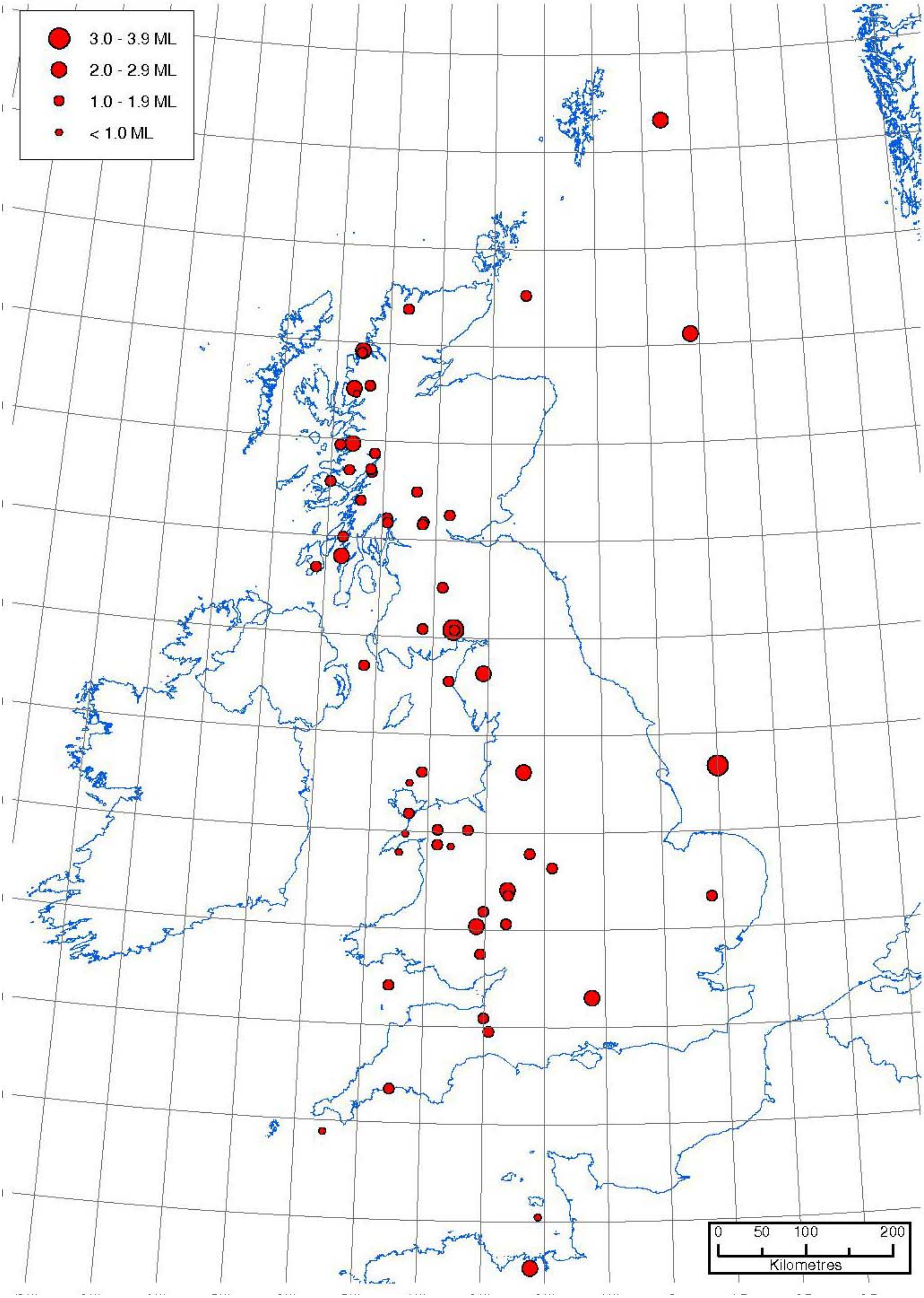
The spatial distribution of seismicity in 2006 generally reflects that observed in the instrumental catalogue as a whole, with the majority of earthquakes occurring in and around Wales, Cornwall, the Midlands, Cumbria, the Scottish Borders and in western Scotland. There was also activity in the northern and southern North Sea.

The largest onshore earthquake of the year, with a magnitude of 3.6 ML, occurred approximately 8 km north-northwest of Dumfries on 26 December at 10:40 UTC, at a depth of 8 km. The largest offshore earthquake occurred in the Norwegian Sea on 18 August, and had a magnitude of 3.8 ML. It was located approximately 360 km north of Lerwick, Shetland Islands. A further four events occurred in the North Sea and surrounding waters during the year, with magnitudes ranging between 2.3 and 3.3 ML.

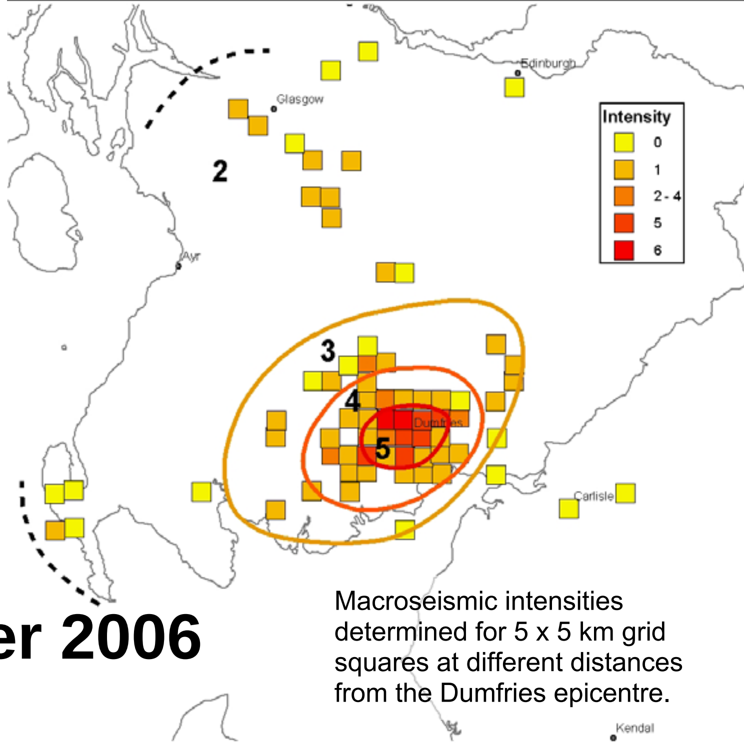
On 12 January 2006 an earthquake with magnitude of 2.6 ML, occurred near Basingstoke, Hampshire. This earthquake is located in an area where only two other earthquakes have been recorded within 25 km of the epicentre. One with a magnitude of 3.0 ML, which occurred on 19 July 1982, was felt with an intensity of at least 4 EMS. The other event with a magnitude of 2.1 ML occurred on 27 July 1985.

The UK monitoring network also detects many 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 2006 to March 2007, a total of 415 teleseismic earthquakes were detected and analysed.

In the following sections, we provide more detailed reports of the magnitude 3.6 ML earthquake near Dumfries, (2006), and the magnitude 4.9 ML earthquake in the North Sea (2007). We also summarise information on some of the destructive earthquakes that have occurred around the world throughout the year.



Epicentres of all UK earthquakes detected in 2006.



Macroseismic intensities determined for 5 x 5 km grid squares at different distances from the Dumfries epicentre.

Dumfries, 26 December 2006

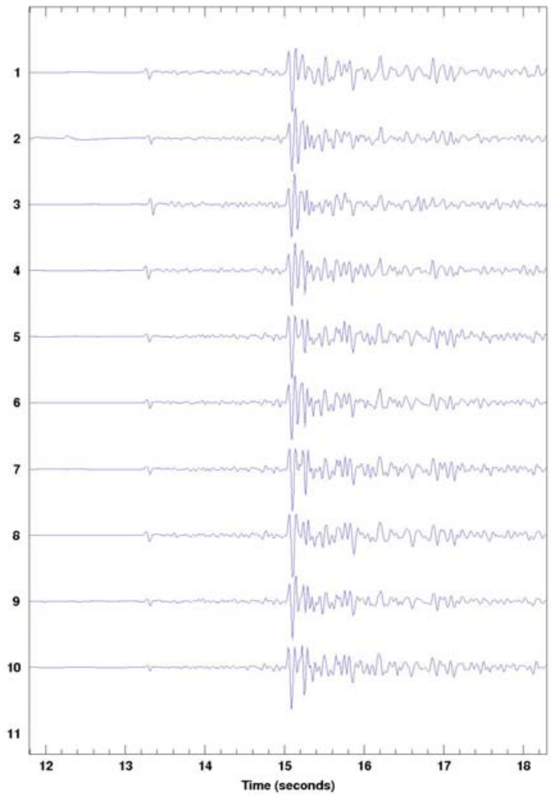
Significant media and public interest was created on 26 December 2006, when a magnitude 3.6 ML earthquake struck Dumfries. Dumfries has experienced numerous small to moderate earthquakes over the past 20-30 years whose epicentres are tightly clustered to the north of Dumfries. The most recent event is no exception and shows strong similarities to previous events.

This earthquake occurred on 26 December 2006 at 10:40 UTC, with an epicentre approximately 8 kilometres north-northwest of Dumfries. The instrumental magnitude was determined at 3.6 ML, and initial reports suggested that the earthquake had been felt throughout southwest Scotland. This earthquake was followed by an event with a magnitude of 1.7 ML with a similar location, on 30 December.

BGS received a number of reports via the media, Dumfries Police and from a number of residents in the Dumfries area of Dumfries & Galloway. A macroseismic survey was launched on the BGS 'Earthquakes' web site, which yielded over 300 replies. The most distant reports were from the southern Glasgow area approximately 100 km away and from the Stranraer area approximately 95 km to the west. The earthquake was felt over an area of 3,600 km^2 for isoseismals 3-5. The highest observed intensity was 5 EMS, which was observed over an area of approximately 230 km^2. The epicentre of this earthquake is in a similar location to the magnitude 3.0 ML Dumfries earthquake of 13 May 2001, which was also felt with intensities of 5 EMS.

A source mechanism for the earthquake was determined from first motion polarities using the grid search method of Snoke *et al* (1984) Fault plane solutions that fit the observed data show a strike-slip mechanism, with either left lateral faulting on a north-northwest south-southeast or right lateral faulting on an east-northeast west southwest fault. Two previous earthquakes in the Dumfries cluster, a magnitude 3.0 ML event on 13 May 2001, and a magnitude 2.3 ML event on 7 August 2004, show very similar source mechanisms.

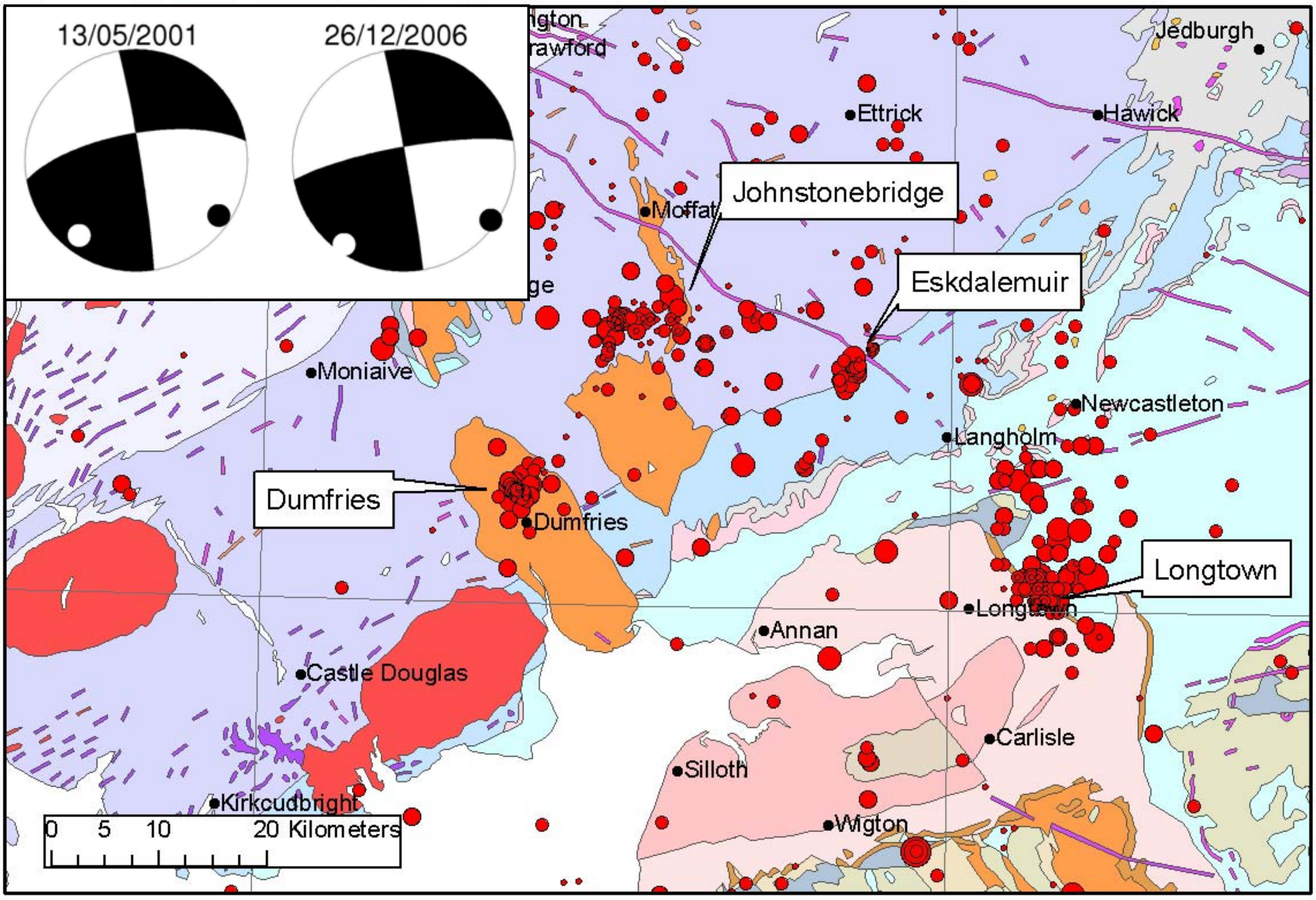
Both possible fault orientations are also consistent with observed fault strikes and offsets. The regional surface geology is dominated by a sequence of major northwest-southeast trending faults that penetrate to the basement and define a series of sedimentary basins several

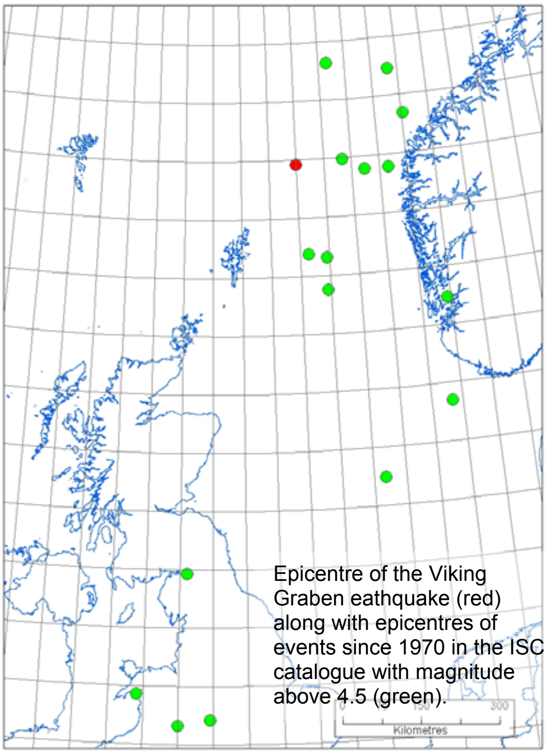


Seismograms recorded at station BWH, showing the similarity between different events in the Dumfries cluster.

kilometres thick. A deeper sequence of faults following a northeast-southeast Caledonian trend is also observed.

Numerous small to moderate earthquakes have occurred in the vicinity of Dumfries over the past twenty years. The BGS catalogue contains forty-nine earthquakes near Dumfries whose epicentres are tightly clustered. Examination of these events show that the waveforms recorded from many of these events are highly correlated, lending further strength to the argument that the events are co-located on either a single or closely linked sequence of faults. Other notable earthquake sequences in this region occurred near Longtown, when an aftershock sequence of over one hundred events followed the magnitude 4.7 ML Longtown earthquake in 1979, and around Johnstonebridge, where over fifty events were recorded between 1985 and 1995. More recently a sequence of forty-one earthquakes occurred southeast of Eskdalemuir between October and December 2004.





Epicentre of the Viking Graben eathquake (red) along with epicentres of events since 1970 in the ISC catalogue with magnitude above 4.5 (green).

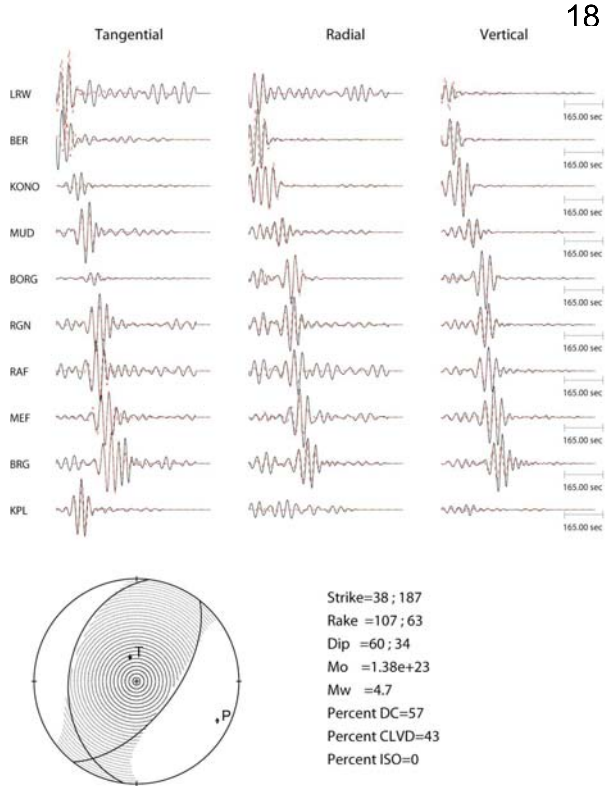
Seismic Activity

The Viking Graben earthquake of 7 January 2007

An earthquake of magnitude 4.7 M_W located in the Northern Viking Graben, about 200 km northeast of Shetland, was the largest in this region to occur during the last decade. The earthquake was felt both in Shetland and on the Norwegian westcoast. This is the first time that an earthquake of this size in this region can be analysed using data from broadband stations from the UK, Denmark and Norway that have been installed over recent years.

The Viking Graben earthquake of 7 January 2007 was the largest earthquake in UK territory since the Bishop's Castle earthquake in 1990. The earthquake remained mostly unnoticed due its offshore location, but was felt on the Shetland Islands and on the Norwegian coast. The earthquake was located on the southern flank of the NE-SW trending North Shetland Spur, a basement high, and was at a distance of about 35 km from the Magnus oil field where it was not felt. However, proximity to installations for hydrocarbon extraction can have hazard implications. As seen from the seismicity map, the Viking Graben and adjacent areas have experienced the largest number of earthquakes with magnitude above 4.5 in north-western Europe. The last earthquake of this size occurred more than 10 years ago, where the coverage with broadband stations was much poorer. The 7 January 2007 earthquake, therefore, is the first earthquake in this region that can be studied using regional broadband data from the UK, Denmark and Norway. Results can lead to a better understanding of the seismo-tectonic setting including the driving forces for earthquakes in the region.

Traditionally, for UK earthquakes, the fault mechanism is determined from first motion polarities. An alternative approach is to use the full waveform signal and invert for the mechanism described by the moment tensor. This approach requires long-period data, normally in the range 10-100sec, which are only reliably recorded by broadband seismometers. Such instruments are being deployed in the UK under the network upgrade programme, and are also available at short distances from the hypocentre in Denmark and Norway, and at larger distances throughout continental Europe. For the moment tensor inversion, we used the method and software of Dreger (2003), which inverts complete waveforms to minimise the difference between observed and calculated waveforms. The synthetic waveforms were calculated based on a velocity model derived from a global surface wave tomography model (http://ciei.colorado.edu/~nshapiro/MODEL; Shapiro and Ritzwoller, 2002) and a global crustal model (Mooney, 1998). The moment tensor inversion can be used to estimate the hypocentre depth, but is only reliable if recordings at relatively short distances are available. Our best result was obtained for a source depth of 10 km and shows a mostly reverse type mechanism with strike=38/187, dip=60/34 and rake 107/63. Distinction between the two nodal planes is not possible, unless additional geological information is available. The waveforms are generally well modelled. Reverse type mechanisms are expected due to the regional compression and have been observed for other earthquakes in the region (e.g, Hicks, 2000).



Observed (black) and modelled (red) seismograms from the moment tensor inversion of the Viking Graben earthquake, along with the lower hemisphere projection of the best-fitting solution.

The moment magnitude of the earthquake is 4.7, which compares well with 4.8 Mb determined by ORFEUS from regional data. The local magnitude determined by BGS is 4.9 ML based on data from the UK and Norway. The magnitude determined by the Norwegian seismic network is 4.2 ML, considerably lower than the BGS magnitude. This discrepancy of ML values highlights difficulties with the ML scales. The scale in use in the UK was originally derived for California, while the scale in Norway was derived from onshore data in Norway. Attenuation is expected to be different for propagation towards the UK in the southwest and towards Norway in the east. The earthquake was located on the western margin of the Viking Graben. Thick sediments within the Graben are expected to lead to higher attenuation towards the east due to scattering. The higher scattering towards Norway can be observed from a comparison of seismograms recorded at Lerwick and Bergen. The Norwegian scale underestimates in this case, as attenuation is higher offshore. The UK scale for this event produces a magnitude similar to a regional body wave magnitude (m_b), which may suggest that it is reasonable for the high attenuation in the North Sea, but then should be overestimating magnitudes of onshore earthquakes in the UK. Work to determine a UK specific magnitude scale has been started and will benefit from on-scale records at short distances measured by the broadband stations.

Seismic Activity

Global Earthquakes

Indonesia was once again struck by a number of damaging earthquakes in 2006/2007. The worst of these struck the island of Java near Yogyakarta. A magnitude 7.7 earthquake south of Java resulted in a devastating tsunami. A Pacific-wide tsunami was generated by a magnitude 8.3 earthquake in the Kuril Islands.

A magnitude 6.3 earthquake on 26 May 2006, near Yogyakarta, Java, resulted in at least 5,749 deaths. Another 38,568 people were injured and more than 578,000 houses were either destroyed or damaged, leaving over 600,000 homeless in the Bantul and Yogyakarta areas. The total loss has been estimated at $US3.1 billion.

The seismicity of Java is related to subduction of the Australian tectonic plate beneath the overriding Sunda plate. However, this earthquake did not occur at the interface between the two tectonic plates, but at a shallow depth in the Sunda plate. Deformation that is not accommodated by slip at the subduction interface results in strike-slip movement along NW-SE or NE-SW trending faults at shallow depths in the overriding plate

A direct link between the May 26 earthquake and the volcano Merapi, some 50 km north of the epicentre, seems unlikely. Merapi had shown signs of increased activity for some weeks before the earthquake, but the earthquake was too large and too far away to have been directly caused by the volcano. However, it is possible that the earthquake may have

destabilised the lava dome on Merapi and could have led to increased surface activity. In addition, stress changes triggered by the earthquake could effect the magmatic plumbing system underneath the volcano. Increased activity has been observed in a number of volcanic regions after large earthquakes. For example, the 1992 magnitude 7.3 Landers earthquake triggered swarms at locations in the western United States.

A magnitude 7.7 earthquake south of Java, on 17 July 2006 resulted in at least 665 people killed, another 9,275 injured, around 1,623 buildings either destroyed or damaged, over 870 boats destroyed and many roads damaged in Jawa Barat and Jawa Tengah. All deaths and damage were as a result of a tsunami that was generated, with maximum wave heights of 4.6m, recorded at Widarapayung.

This earthquake resulted from thrust faulting at the boundary between the Australian and Sunda plates.

Two earthquakes within two hours struck the island of Sumatra on 6 March 2007 with magnitudes of 6.4 and 6.1. At least 70 people were killed and hundreds were injured, with severe damage in the Bukittinggi-Solok-Payakumbuh area.

The locations and focal mechanisms of both earthquakes are consistent with these shocks occurring on the Sumatran fault, a 1900 km-long strike-slip fault that extends the length of the island.

The central part of the Sumatra Fault has a history of producing double events on the same day. In 1926, two earthquakes within three hours and with magnitudes of around 6.5 occurred in a similar location to the 2007 earthquakes. In 1943, two earthquakes with magnitudes of 7.2 and 7.5 occurred within seven hours of each other. This may suggest that the Sumatra Fault is highly segemented, with adjacent segments failing together.

Damage caused by the magnitude 6.3 earthquake on 26 May 2006, near Yogyakarta (Earthquake Engineering Research Institute/ Juan Chavez),

Scientific Objectives

Seismotectonics and Stress

A comprehensive catalogue of earthquake focal mechanisms has been compiled. These can be used to help us understand the nature of deformation and the driving forces for earthquake activity in the UK.

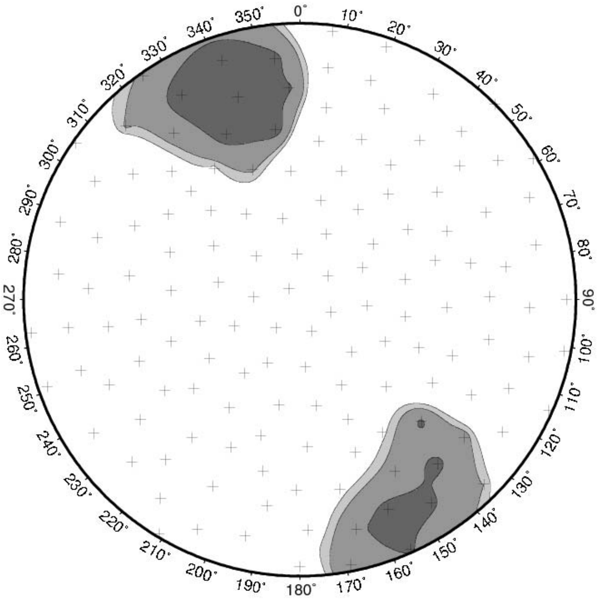
The underlying cause and distribution of earthquake activity in the British Isles is not clearly understood. Main et al. (1999) suggest that the observed neotectonic uplift combined with a direction of maximum (regional) stress deduced from earthquake focal mechanisms supports the theory that deformation 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. A comprehensive catalogue of focal mechanisms for British earthquakes with magnitudes of ≥ 3.0 ML has been prepared for the first time. The fault plane solutions consist of both previously published mechanisms for significant British earthquakes, for example Trodd et al (1985) and new solutions calculated from local recorded data for more recent and smaller earthquakes that were previously unpublished.

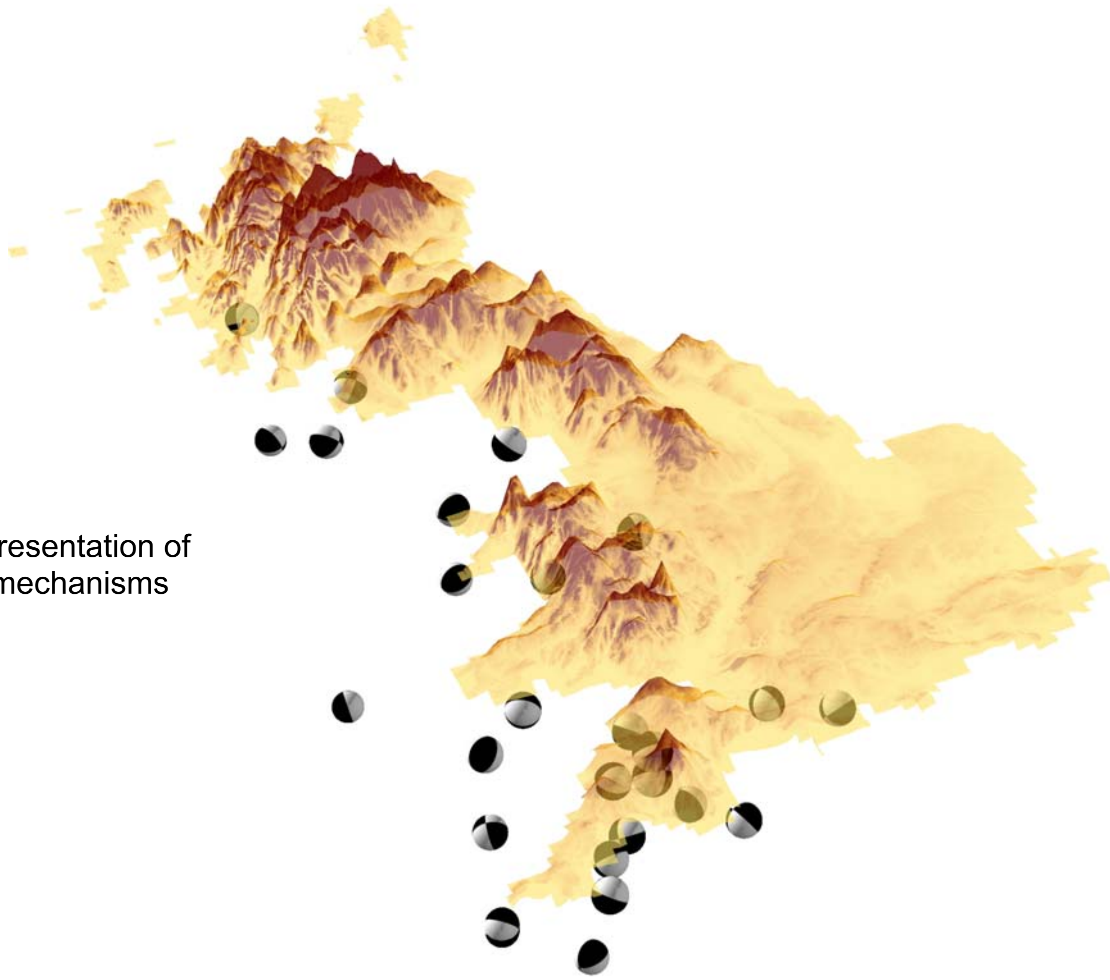
Our catalogue contains twenty-eight high quality focal mechanisms, where both focal planes are well constrained, that can be used in subsequent interpretation and analysis. The focal mechanisms are mainly strike-slip with northwest-southeast compression and northeast-southwest tension, or reverse, with northwest-southeast compression. In many cases there is also an oblique component to the slip. This results in dips for the P axes (maximum compression) that are sub-horizontal, while the T axes (maximum tension) vary from horizontal to vertical. The P-axes orientations for most events cluster between north and northwest. However, there is clearly some spatial variation in P-axes orientation between north and south, with a preferred near north direction in Scotland, changing to a more northwest orientation in England and Wales.

The hypothesis that these fault plane solutions can be explained by a single uniform stress tensor orientation has been tested by inverting the focal mechanism data to estimate a best-fitting stress tensor for the UK under the assumption of uniform stress. Two different methods of stress tensor inversion are used: Gephart and Forsyth (1984) and Michael (1987). Since each focal mechanism has two possible fault planes and slip direction, both methods also attempt to distinguish between the fault plane and the auxiliary plane. All solutions are given equal weighting in each inversion.

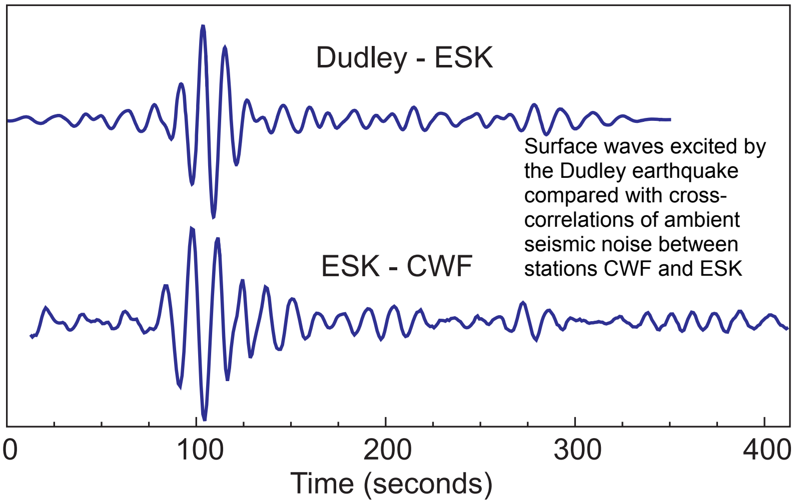
The Gephart and Forsyth (1984) method gives the best-fitting trend and plunge of each of the principal stresses as σ_1 =(343,21), σ_2 =(91,39) and σ_3 = (231,44). The Michael (1987) method gives the best-fitting trend and plunge of each of the principal stresses as σ_1 =(336,9), σ_2 =(101,75) and σ_3 = (244,44). The relative magnitude of the principal stresses is given by the parameter R= $(\sigma_3 - \sigma_1)/(\sigma_2 - \sigma_1)$. Both methods give R = 0.6, which 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 (sphere stretched along a NW-SE axis).



Results of the inversion of the full data set using the Gephart and Forsyth method Inversion results showing showing the 95%, 90% and 67% confidence intervals



A 3-D representation of UK focal mechanisms



Surface waves excited by the Dudley earthquake compared with cross-correlations of ambient seismic noise between stations CWF and ESK

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 3-D 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.

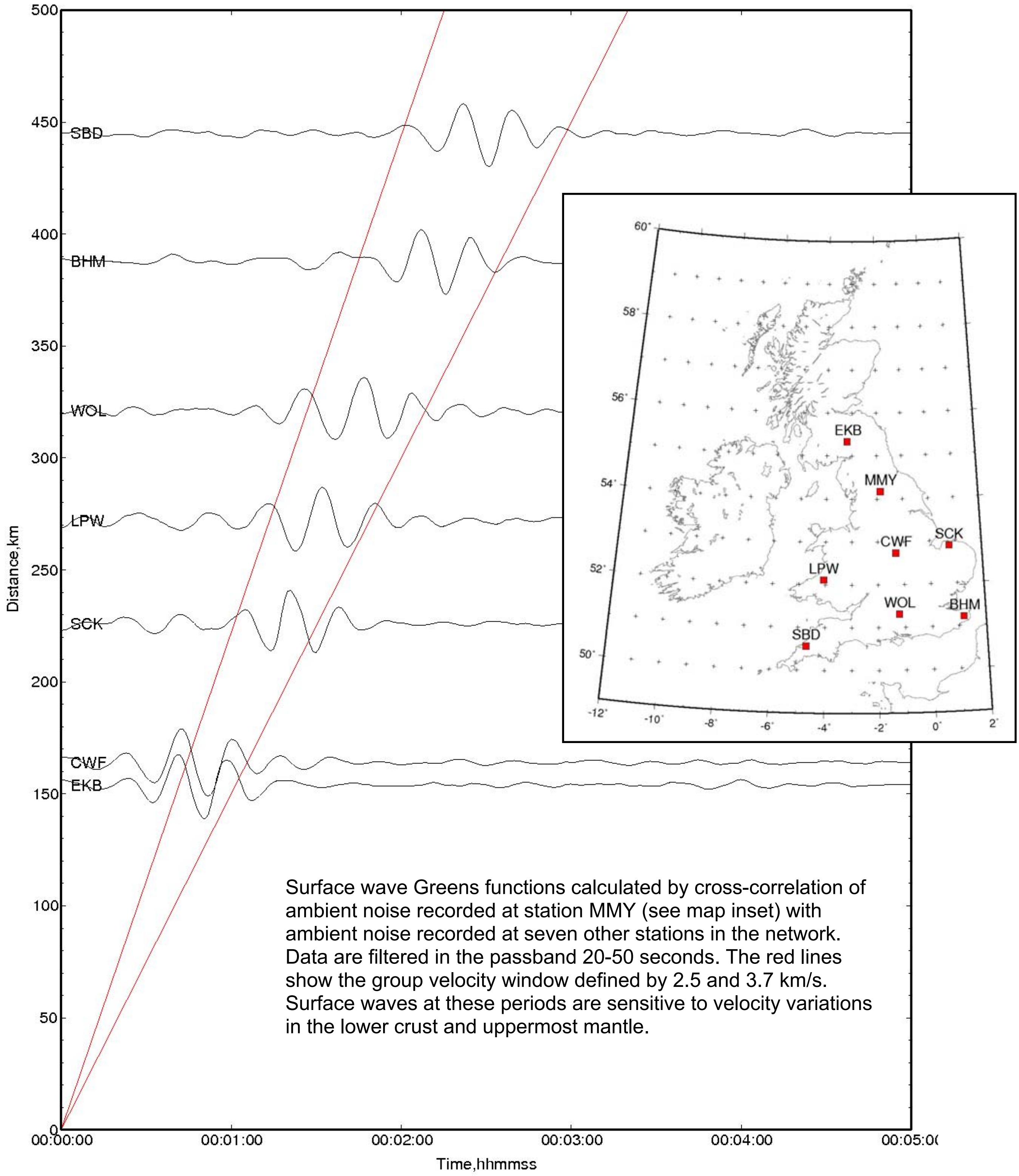
Recent advances in theory (e.g. Wapenaar, 2004) have shown that the cross-correlation of the random wavefield between two seismic stations can provide an estimate of the Green's function between the stations. This has been confirmed using seismic data (Shapiro and Campillo, 2004). This approach can be particularly useful in areas such as the UK where there are relatively few "active" sources.

We have tested application of this method using data recorded at broadband seismic stations across the UK. Firstly, by comparing the surface waves excited by the 2002 Dudley earthquake recorded at the seismic station ESK and the stacked cross-correlation functions computed from 24 hour segments of data between stations CWF (relatively close to the Dudley epicentre) and ESK. The similarity between the two signals confirms the validity of the method.

Secondly, we have used data from the AWE network of broadband stations that operated from 1970-1998 to construct surface wave Greens functions from the continuous data recorded at pairs of stations. Twelve-hour segments of continuous data were firstly decimated, filtered using a number of different pass-bands, 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 month. The resulting stacks show stable waveforms whose character is consistent with Rayleigh waves propagating between the two stations. For example, arrival times at different stations are consistent with

Rayleigh waves propagating at typical group speeds within the crust.

The next stage of this work will be to invert surface-wave group and phase velocities obtained along the different station-to-station paths to produce 2-D maps of velocity variations for different periods of surface waves across the UK. Different periods are sensitive to velocity variations at different depths in the crust. As more broadband data is collected at new stations, this can be added, to improve the resolution of the final model.



Surface wave Greens functions calculated by cross-correlation of ambient noise recorded at station MMY (see map inset) with ambient noise recorded at seven other stations in the network. Data are filtered in the passband 20-50 seconds. The red lines show the group velocity window defined by 2.5 and 3.7 km/s. Surface waves at these periods are sensitive to velocity variations in the lower crust and uppermost mantle.

Scientific Objectives

Has the UK Experienced a Major Earthquake in Historical Times?

A recent BGS study (Musson 2006, 2007) has addressed the question: could a major earthquake have struck the UK in historical times and would it have been recognised?

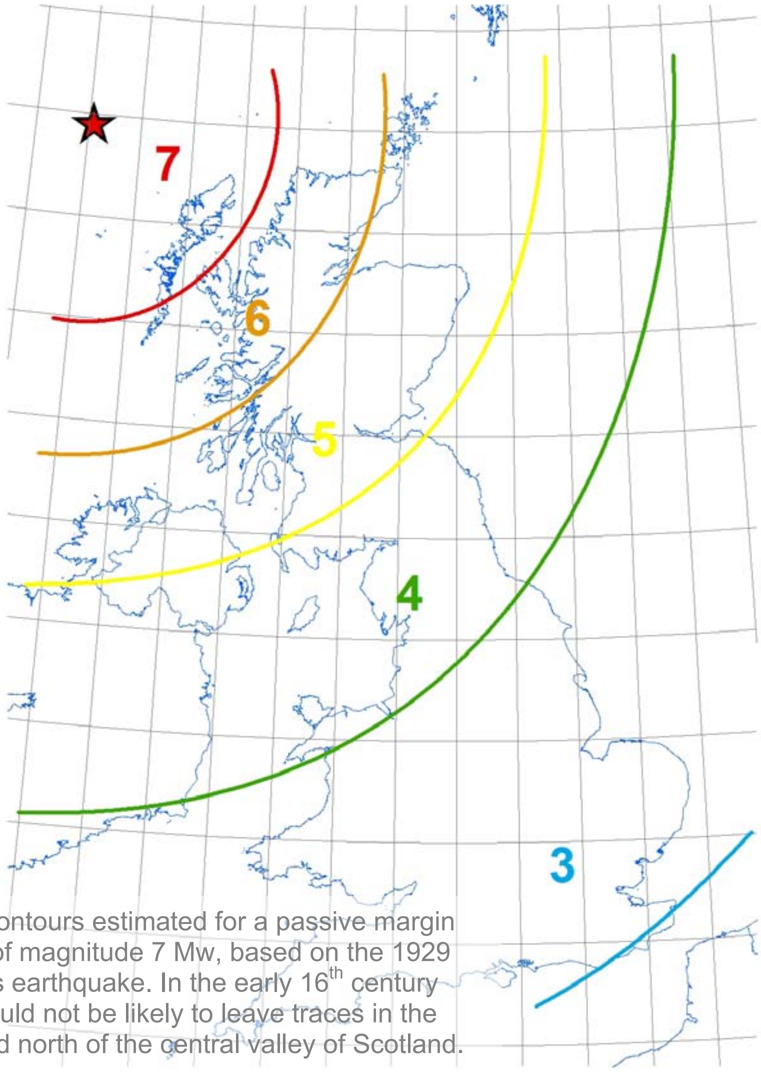
A perennial question in discussing seismic hazard in the UK is the problem of what is the largest earthquake that could directly affect the British Isles. Maximum magnitude is difficult to assess for low seismicity areas, where the seismic cycle is most likely much longer than the historical record. Any assumption that low seismicity means no large earthquakes is shattered by examples from other parts of the world, where earthquakes in excess of magnitude 7 Mw have occurred in areas that otherwise have little, or even no seismicity. Examples are the 1811-1812 New Madrid sequence in the central United States and the 1929 Grand Banks earthquake off the coast of Newfoundland.

One can make a reconstruction of what might have been the effects had something similar to the 1929 Grand Banks earthquake occurred in the early historical period, with a hypothetical location in the vicinity of the Wyville Thompson Ridge where there is some evidence suggestive of recent faulting (Tate 1992). Transposing the 1929 isoseismals (Smith 1966), one can get an idea of what would most likely have occurred, and from historical knowledge one can imagine how this would have been reported.

The strongest, damaging effects, would have been confined to the NW Scottish Highlands, a remote Gaelic-speaking area with no written tradition. For an earthquake before the17th century it is unlikely that any record would survive. One would expect some written notice from the Central Valley and Scottish Lowlands, but over this area the intensity would be 5 EMS (European Macroseismic Scale), in other words, strong, alarming, but not damaging.

For England, where the historical record is much better than for Scotland, the earthquake would be felt more or less uniforMLy at around 4 EMS (generally perceptible). So the most that one could expect as a historical record would be that an earthquake was felt all over England. (This is a description that appears, without further detail, for a number of medieval earthquakes.)

There exists one earthquake that fits this pattern rather well. It occurred on 18 September 1508 and is very poorly documented, being known from only three



Isoseismal contours estimated for a passive margin earthquake of magnitude 7 Mw, based on the 1929 Grand Banks earthquake. In the early 16th century the event would not be likely to leave traces in the written record north of the central valley of Scotland.

authors. The salient points about this earthquake are as follows:

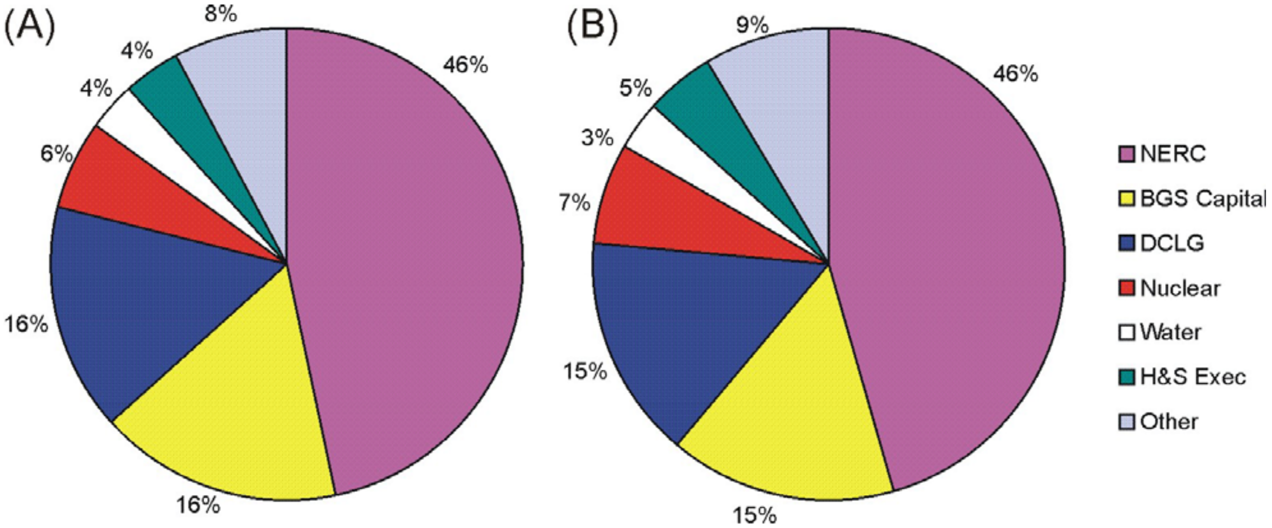
1. It was said to have been felt all over Scotland and England.
2. It is reported more in Scottish sources than English ones, suggesting it was stronger in Scotland.
3. Despite the large felt area, no damage is mentioned.
4. It is described as having been alarming.
5. It is said to have lasted six minutes. While estimated durations are notoriously unreliable, and often include the duration of aftershocks, this clearly suggests that the main shock shaking was quite long.
6. It is described as being particularly strongly felt in churches. One can speculate that this was due to the better spectral response of tall churches to the effects of a large distant event.

There is no mention of the event in Irish sources, but these are not particularly good for the period.

Thus the evidence, while limited, is entirely compatible with a major earthquake of around 7 Mw having taken place off the NW coast of Scotland, on the continental margin.

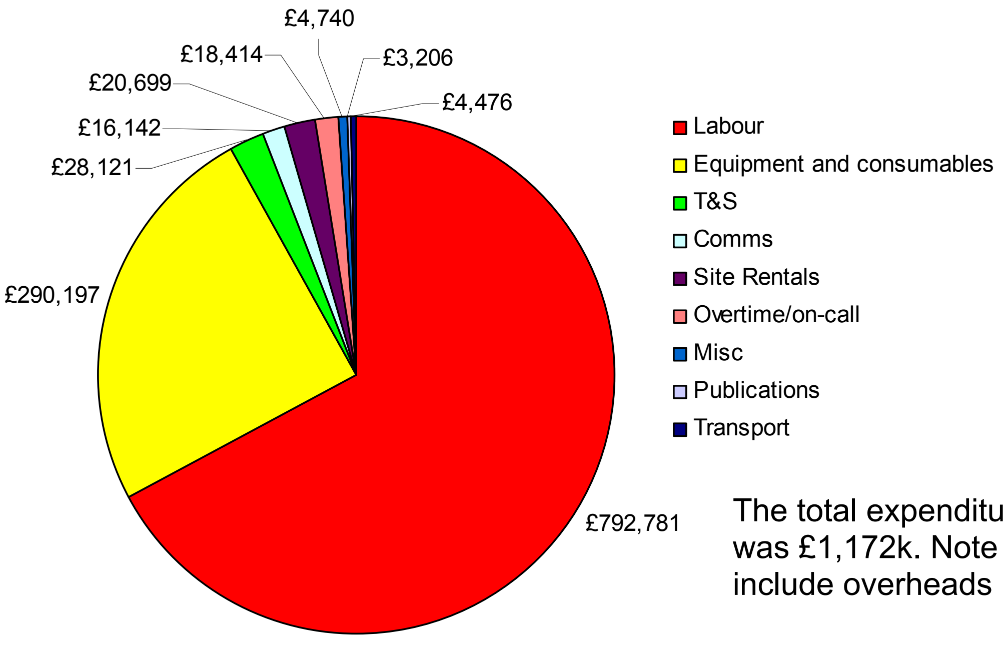
Funding and Expenditure

In 2006-2007 the project received a total of £594k from NERC. This was matched by a total contribution £467k from the customer group drawn from industry, regulatory bodies and central and local government. In addition, BGS management have recognised that the network needs to be upgraded to improve both monitoring and quality of science. In 2006-2007 we received £210k of capital funding to purchase new instrumentation and improve station and network infrastructure.



Pie charts showing project funding. The total funding received in 2006/2007 was £1.27 million. Projected funding for 2007/2008 amounts to £1.29 million.

The projected income for 2006-2007 remains approximately the same. The level of funding from NERC remains almost the same at £593 k. We also hope to secure a further £200k of BGS capital funds to continue with the upgrade of the monitoring network. The Department for Communities and Local Government, DCLG, has pledged continued support for the project for the next five years to 2011.



The total expenditure for 2006/2007 was £1,172k. Note that labour costs include overheads

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 Executive Director of the British Geological Survey (NERC).

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Appendix 1 The Project Team

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Alice Walker	UK & Regional Seismicity
Susanne Sargeant	Seismic Hazard
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Richard Luckett	Seismic Data Processing
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Simon Flower	Senior Software Engineer
Dave Scott	Software Engineer
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Appendix 2 Publications

BGS Internal Reports

Baptie, B. 2006. Earthquake Monitoring 2005/2006, BGS Seismic Monitoring and Information Service, Seventeenth Annual Report, BGS Internal Report IR/06/098.

Holmes, R., K. Hitchen and L. Ottemöller. Strategic Environmental Assessment Area 7: hydrocarbon prospectivity, earthquakes, continental shelf surficial and seabed geology and seabed processes, British Geological Survey, Commissioned Report, CR/06/063, 2006.

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

External Publications

Booth, D.C., 2007. An improved UK local magnitude scale from analysis of shear- and Lg-wave amplitudes, Geophys.J.Int., 169, 593-601.

Hardwick, A.; England, R.; Maguire, P.; Baptie, B.; Ottemoller, L. 2006. 3D Local Earthquake Tomography of England and Wales, American Geophysical Union, Fall Meeting 2006.

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Appendix 3 Publication Summaries

An improved UK local magnitude scale from analysis of shear and Lg-wave amplitudes

D.C. Booth

The amplitudes of shear and Lg waves recorded at UK seismograph stations from local earthquakes in the range 0-600 km have been subjected to an analysis of variance, allowing separation of the effects of earthquake size, distance and station corrections for each recording site. The propagation paths sample mainly the central to western part of the UK, with good north-south coverage. The analysis of 385 amplitude readings at 28 stations from 40 earthquakes showed that the effects of both distance and station (site) corrections were statistically significant. Tables of corrections for both distance and station effects have been derived to allow local magnitude ML to be determined more accurately from horizontal and vertical component records. One set of tables allows the estimation of an ML which is consistent with the original Richter definition of ML, with a standard deviation which is smaller than that produced by the theoretical attenuation curve, defined according to attenuation in Southern California, which has customarily been used to calculate ML in the UK. The reduction in standard deviation is mainly due to the incorporation of station terms to correct for station effects, since the theoretical and observed variations of attenuation with distance are similar. This similarity implies that Southern California and the UK show a similar variation of distance-dependent attenuation for Lg waves, which was not expected in view of the differences in geology and tectonics. Another set of tables is provided to calculate an ML which is consistent with the body wave magnitude mb determined by the International Data Centre from station records of the Comprehensive Test-Ban Treaty Organization's global monitoring network. The decay with distance of the predominantly Lg-wave amplitude values gives a value of 440 ± 50 for LgQ at a frequency of 3 Hz, in agreement with estimates obtained from spectral displacement amplitudes of Lg waves in the UK.

3D Local Earthquake Tomography of England and Wales

A. Hardwick, R. England, P. Maguire, B. Baptie and L. Ottemoller

For the past three decades crustal studies of the British Isles have been restricted to the interpretation of 2-D seismic reflection and refraction profiles, mostly aquired offshore. The British Geological Survey (BGS) seismic monitoring network has grown substantially over the past twenty years to a density and quality unprecedented for an aseismic region. Recently, this has made it possible to undertake teleseismic studies to image the seismic velocity of the mantle via 3-D tomography and 1-D receiver functions for the crust and uppermost mantle. Whilst the British Isles can be considered an aseismic region by world standards, the BGS network typically records 40 local events of over 2.0 on the local magnitude scale every year. Irrespective of an intra-plate setting, the width of seismogenic zone is exceptional, ranging from the surface to in excess of 30 kilometres depth despite no surface ruptures ever having been observed. For the first time we utilise these locally generated seismic events within the BGS digital catalogue recorded over the past two decades to produce a model of seismic P- and S- velocity to depths of 70 km beneath England, Wales and the Irish Sea at an unmatched resolution. A high quality subset of over 1,000 local events and 18,000 arrival times has been extracted from the entire digital catalogue. This has been used to relocate the events with a 1-D seismic P-velocity model extracted from a regional 2-D model derived by extrapolation of wide-angle refraction profiles. The initial locations and 1-D model have been simultaneously updated and refined using VELEST to produce a consistent set of station corrections for the BGS network which is in good agreement with known geology. The updated locations and 1-D model acts as the reference model for a 3-D tomographic model developed with the SIMULPS inversion code. Our 3-D model will compliment teleseismic and controlled source studies which demonstrate seismic anomalies thought to be associated with the emplacement of magmatic underplate beneath the East Irish Sea. We note that the earthquakes are distributed around the edges of this high velocity and high density body which suggests that they may be related of loading on the crust.

Automatic assessment of EMS-98 intensities

R.M.W. Musson

This report presents a proposal for the basis of an automatic system for assigning EMS-98 intensity values to questionnaire data gathered from a web page. Such systems have been proposed in the past and are in use in some countries. That proposed here operates in a manner designed to mimic human reasoning in assigning intensities.

Webb's observations of earthquakes

R.M.W. Musson

Amongst the papers of the Victorian astronomer TW Webb is a small soft-backed notebook measuring approximately 18 x 12 cm. On the cover is written "Miscellaneous Observations by TW Webb"; underneath this is a date, 1874, and under this is written "NB There are more note worthy observations in this little book than might be inferred from its appearance". On the back cover and inside the front cover are jotted a few financial sums. This book contains jottings made between 1874 and 1883 on various natural phenomena, such as unusual meteorological conditions. In amongst these are a large number of reports of earthquake vibrations being felt by Webb and his wife at Hardwick (or Hardwicke) Vicarage. These latter are of particular interest today because of the importance of studying historical earthquakes in order to be able to estimate future hazard. In this chapter of a biography of Webb, the earthquake observations are transcribed and discussed.

The enigmatic Bala earthquake of 1974

R.M.W. Musson

The earthquake that shook most of North Wales on the night of 23 January 1974 appears unremarkable from its entry in the UK earthquake catalogue. With a magnitude of 3.5 ML it represents the size of earthquake to be expected in the UK with a return period of about one year. However, the prominent atmospheric lights observed at the time of the shock led at the time to speculation that an aircraft had crashed, and search-and-rescue teams were deployed. Since nothing was discovered, it was concluded that a meteorite was responsible; more imaginative members of the public decided (and still believe) that a UFO had crashed. In this paper the record of events is set out, and the nature of the earthquake is discussed with reference to its geological setting.

On the perceptibility of earthquakes

R.M.W. Musson

A method is presented to derive a first order approximation of the number of people likely to feel any earthquake, assuming a uniform population distribution. The “most perceptible” earthquake is a function of the frequency of earthquake occurrence (there are more small earthquakes) and effect (large ones will be felt by more people). The method is demonstrated taking the UK as a test case. The trade-off between the two trends seems to produce a peak value of about 4.5 ML for the earthquake that the typical inhabitant of the UK is most likely to have felt. It is also found that a UK citizen who lives for 70 years has a roughly 42% chance of experiencing a British earthquake at some point in their life. In practice, of course, the issue is complicated both by irregular population distribution and to some extent regional irregularities in the magnitude-frequency distribution for the UK. The method is easily adaptable to other countries; its relevance is chiefly in the generation of statistics of interest to the public at large, thus aiding public understanding of science.

The geology and geophysics of the United Arab Emirates, Volume 4: Geological hazards

R.M.W. Musson, K.J. Northmore, S.L. Sargeant, E.R. Phillips, D. Boon, D. Long, K. McCue and N.N. Ambraseys

The UAE represents an area where the threat from local earthquakes is very small, but there is a real threat from large, fairly distant events. The Arabian Peninsula is extremely stable, albeit not completely aseismic, but earthquakes to the north in southern Iran are of concern, especially as regards ground motion at longer spectral periods. As part of a recent major geological project in the UAE, we have compiled a series of seismic hazard maps for the country. These maps are based on a new earthquake catalogue with reassessed parameters, including some new historical earthquakes not previously known, and also on a thorough investigation of the geology and tectonics of the UAE territory. The conclusions of are study are, firstly, that the main source of hazard is a zone of strong seismicity around Qeshm Island and Bandar Abbas (and stretching north-east from there), though maximum magnitudes seem to be capped at around 7 Mw. Secondly, there is a potential for local seismicity in the east of the UAE in the area affected by the 2002 Masafi earthquake, but there is no geological support for the idea that there is a major active fault running through Dibba. Nor is there evidence for a seismically capable fault running through the cities of the west coast of the UAE. Thirdly, we are very doubtful that the western part of the Makran represents an active subduction zone. The chief evidence for this seems to be an earthquake in 1483 which we have relocated further west. The cumulative effect of these conclusions is that the seismic hazard in the UAE is actually rather low. It is very substantially lower than that shown in the GSHAP global map, in which it appears that the hazard for the UAE was drawn in ad hoc rather than calculated probabilistically. As well as producing hazard maps for the country, we have also derived some sample hazard curves and uniform hazard spectra from the same seismic model. Other geological hazards (landslides, liquefaction) are also described.

Conversions between older intensity scales and EMS-98

R.M.W. Musson, G. Grünthal and M. Stucchi

Ideally, direct conversion between intensity scales should never be made. The correct procedure is always to reassign intensity values to the original data using the desired scale. However, there are many cases where this is not practical, and some guidance is needed to convert data from older scales to newer ones. The problem is that any set of intensity values is a compound of the scale used and the working practices used, and the latter are usually undefined and obscure. Thus, intensity values are likely to vary more between two seismologists using the same scale than between two scales used by the same seismologist (at least for twelve-degree scales). It follows that comparison of sets of assigned values using different scales will give insight into those data sets, but will probably not reveal general relationships between the two scales. To get a general picture of the equivalence between two scales, the best procedure is to treat the definition of an intensity degree in scale A as if it were data, and assign a value to it using scale B. Following this procedure, the relationship between major twelve-degree scales (such as MSK, MMI and MCS) and EMS-98 is more or less 1:1. The chief difference between these scales is not so much the level of shaking represented by each degree, but the extent to which the wording of the scale guides the user to make the correct intensity assignment. Thus intensity values that have been assigned using (say) MMI and then converted to EMS-98 will not be as reliable as those assigned directly using EMS-98.

EMS-98 as a tool for loss estimation

R.M.W. Musson

For the purpose of estimating earthquake loss to a large assemblage of buildings (as opposed to a single building), approaches using physical parameters of earthquake ground motion are affected by the quality of the correlation between strong ground motion and damage. In addition, expected ground motion from a future earthquake at a site is subject to lognormal scatter. A robust alternative is to use intensity in place of physical ground motion parameters. An intensity attenuation equation is essentially a numerical description of the probability of damage to buildings as a function of distance and magnitude, derived directly from past observations of damage. Furthermore, intensity data are more copious for many parts of the world than are strong ground motion records, so locally validated intensity attenuation equations are more easily found than those for peak ground acceleration or velocity. EMS-98 is particularly appropriate for this type of use because of its probabilistic basis; each degree of the scale can be represented by the expected distribution of damage grades to buildings of different vulnerabilities. Implementing a simulation-based approach to loss estimation provides a straightforward way to estimate general expected loss levels to large assemblages of normal domestic buildings. The main limitation is that losses to special structures such as bridges, skyscrapers or industrial plant cannot really be obtained in this way.

Impact of epistemic uncertainty on seismic hazard estimates

R.M.W. Musson

Epistemic uncertainty in seismic hazard is defined as uncertainty about things that have a true value which is unknown, contrasted with aleatory uncertainty, which is the uncertainty about things that are unknowable, because they pertain to random processes. One can imagine a situation where one has to estimate the number that will be rolled on an unknown number of dice. The person rolling the dice knows the number of dice, but for the estimator this is epistemic uncertainty. If the estimator were able to find out the number of dice, this epistemic uncertainty would be removed, but the actual number to be rolled could still not be predicted because of the irreducible aleatory nature of dice throws. Estimating fully the epistemic uncertainty in a seismic hazard model is considered to be important in order to express the uncertainty in the final hazard results (typically as a suite of percentile hazard curves). But what effect does epistemic uncertainty have on the actual value of the hazard results – specifically the value that will be carried through into the design process? Potentially, epistemic uncertainty could be symmetrical about the best estimate value in such a way that the overall impact is small. Some typical cases are examined.

Possible extreme UK earthquake events hidden in the historical record

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. However, in no case is such an interpretation the only one viable. Also, some cases that 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. Thus the regional maximum magnitude may be larger than has hitherto been assumed.

Highland Boundary Fault Zone: Tectonic implications of the Aberfoyle earthquake sequence of 2003

L. Ottemöller and C.W. Thomas

The Highland Boundary Fault Zone (HBFZ) is one of the major faulted tectonic boundaries in Great Britain. Historically, seismicity has occurred in this zone around the town of Comrie. But an earthquake sequence that occurred in 2003 near the village of Aberfoyle (ML 1.3–3.2) was the first significant activity to be recorded in the HBFZ since the installation of modern seismograph networks in the 1970s. This study describes detailed analysis of these data. The waveform signals of the events were almost identical and by applying a cross-correlation technique combined with multiple event location, the alignment of the events was found to be WSW–ENE. This alignment matches one of the nodal planes determined by joint focal mechanism analysis. The fault plane dips to the northwest, and shows oblique sinistral strike–slip with normal movement. The orientation of the event alignment matches the direction and orientation of observed features in the HBFZ. Hence, it is concluded that the WSW–ENE striking nodal plane was the causative fault that is associated with the HBFZ. The orientation of maximum compressional stress is rotated from the regional average expected due to the Mid-Atlantic ridge-push force. This rotation is possibly explained by stresses due to postglacial rebound. Smaller events in the sequence were used as empirical Green's functions and deconvolved from the larger events to determine source time functions. The corresponding corner frequencies matched results from spectral fitting, showing that the events were of relatively low stress drop.

QLg Tomography In Britain

S. Sargeant, L. Ottemöller

Lateral variations in Lg-wave propagation in and around mainland Britain have been investigated using short period recordings from the UK Seismic Network. The dataset consists of 30 crustal earthquakes (2.7-4.7 ML) recorded in the distance range 170-600 km giving a total of 510 ray paths. The study area is generally well sampled with the exception of northernmost Scotland and southeast England. The regional average Lg quality factor, QLg, was estimated between 0.5 and 7.0 Hz. The result indicates that attenuation in mainland Britain is similar to levels observed in France and provides valuable information for ground motion simulation in the UK. The lateral variation in QLg was solved as a mixed-determined inverse tomography problem following the methodology of Ottemöller et al. (2002). Tomographic inversions were conducted individually for 23 frequencies in the range 0.5-7.0 Hz. The spatial resolution obtained was around 100 km in areas with good data coverage. Lower than average QLg values were obtained for the collision zone associated with the closure of Iapetus, which lies between the Highland Boundary Fault and a major shear zone in northern England. Low QLg values were also obtained for the Anglo-Brabant Massif region whereas the older Welsh Massif appears to be characterised by high QLg. The results point towards similar attenuation north and south of the Great Glen Fault in Scotland and the Variscan Front in southern England but these areas are not well resolved.

Analysis of the crustal velocity structure of the British Isles using teleseismic receiver functions

J.P. ToMLinson, P. Denton, P.K.H. Maguire and D.C. Booth

The onshore crustal and upper mantle velocity structure of the British Isles has been investigated by teleseismic receiver function analysis. The results of the study augment the dense offshore and sparse onshore models of the velocity structure beneath the area. In total almost 1500 receiver functions have been analysed, which have been calculated using teleseismic data from 34 broadband and short-period, three-component seismic recording instruments. The crustal structure has primarily been investigated using 1-D grid search and forward modelling techniques, returning crustal thicknesses, bulk crustal Vp/Vs ratio and velocity-depth models. H-? stacking reveals crustal thicknesses between 25 and 36 km and Vp/Vs ratios between 1.6 and 1.9. The crustal thicknesses correlate with the results of previous seismic reflection and refraction profiles to within ±2 km. The significant exceptions are the stations close to the Iapetus Suture where the receiver function crustal thicknesses are up to 5 km less than the seismic refraction Moho. This mismatch could be linked to the presence of underplated magmatic material at the base of the crust. 1-D forward modelling has revealed subcrustal structures in northern Scotland. These correlate with results from other UK receiver function studies, and correspond with the Flannan and W-reflectors. The structures are truncated or pinch out before they reach the Midland Valley of Scotland. The isolated subcrustal structure at station GIM on the Isle of Man may be related to the closure of the Iapetus Ocean