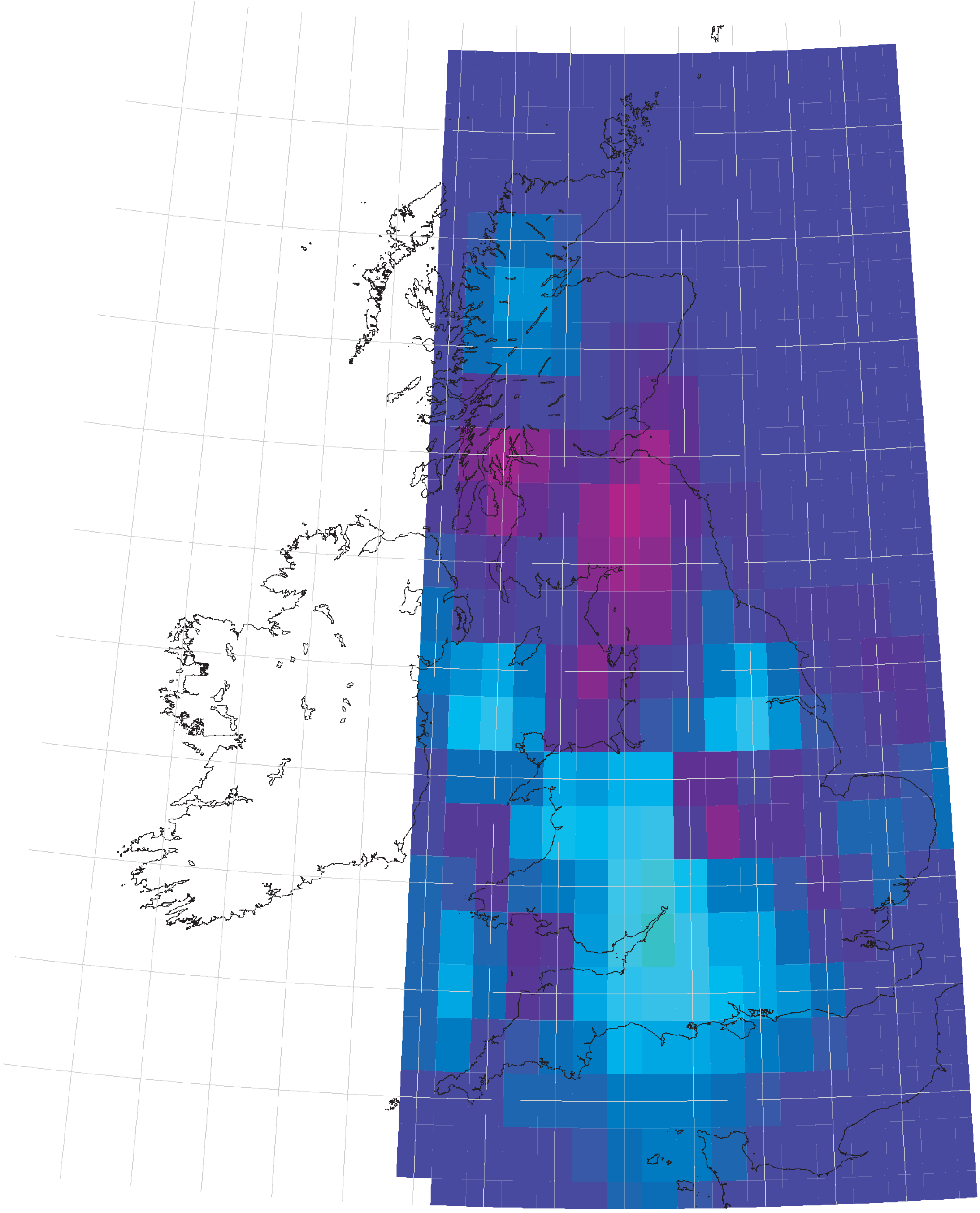
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Earthquake Monitoring 2005/2006

BGS Seismic Monitoring and Information Service

Seventeenth Annual Report



BRITISH GEOLOGICAL SURVEY

COMMISSIONED REPORT IR/06/XXX

UK Earthquake Monitoring 2005/2006

B. Baptie (editor)

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Summary

The British Geological Survey (BGS) operates a network of seismograph stations throughout the UK in order to acquire standardised data on a long-term basis. The aims of the Seismic Monitoring and Information Service are to develop and maintain a national database of seismic activity in the UK for use in seismic hazard assessment, and to provide near-immediate responses to the occurrence, or reported occurrence, of significant events. The project is supported by a group of organisations under the chairmanship of the Office of the Deputy Prime Minister (ODPM) with major financial input from the Natural Environment Research Council (NERC).

In the 17th year of the project three new broadband seismograph stations were established, giving a total of nine broadband stations. Communications to the broadband station at Michaelchurch were upgraded by installation of a satellite link. Real-time data from all broadband stations are being transferred directly to Edinburgh for archival and storage. Near real-time data from short period stations in our Devon, South East England, Eskdalemuir, Lownet and Kyle seismic networks are now being transferred directly to Edinburgh, where they have been incorporated into automatic detection and location schemes. Upgrade of the monitoring network remains our major goal. We have purchased a further fourteen 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 (Galloway, 2006). In all reporting areas, scheduled targets have been met or surpassed.

Eight papers have been published in peer-reviewed journals and three presentations were made at international conferences. Three BGS internal reports were prepared along with five confidential reports.

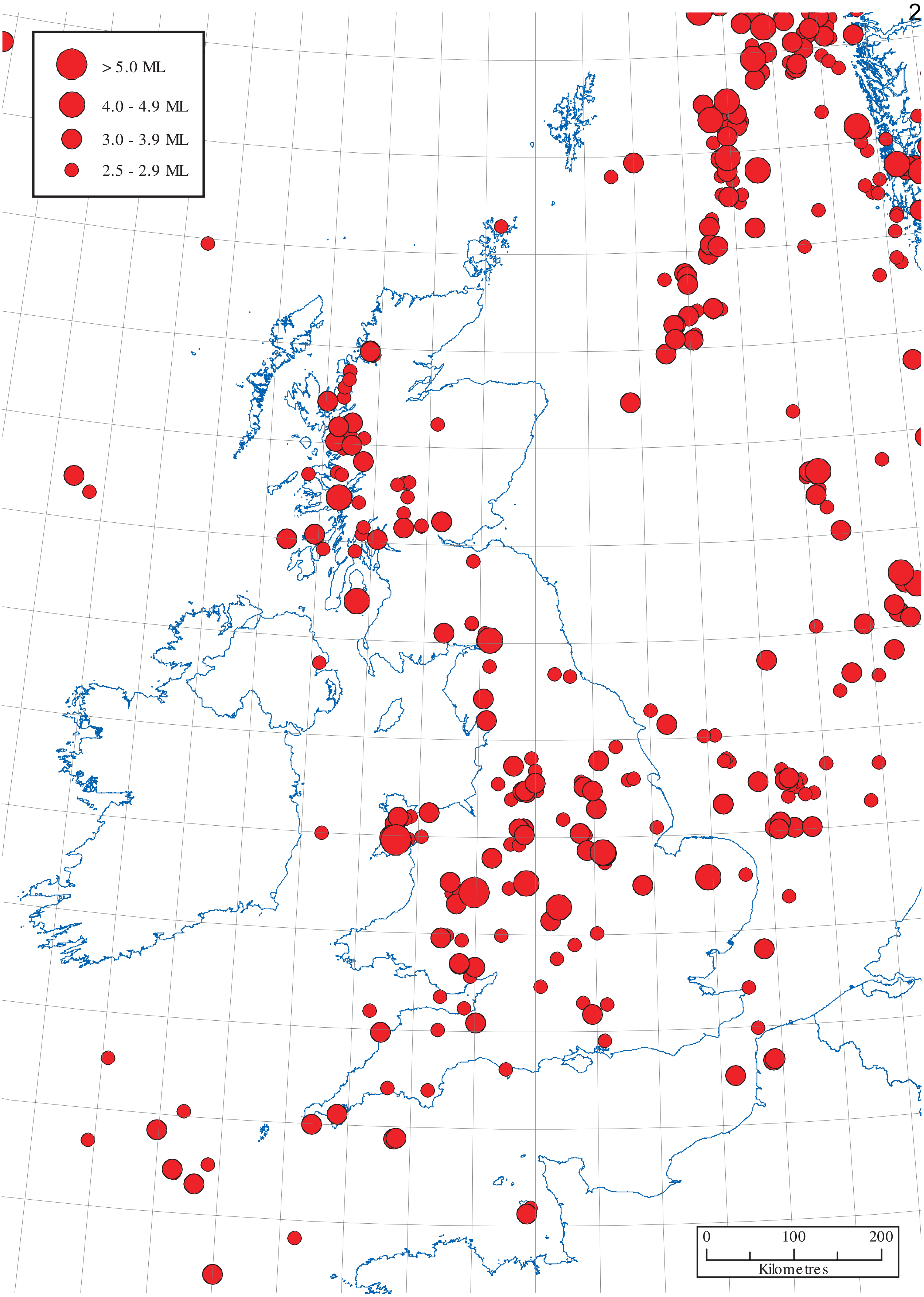
Introduction

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 200 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. 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. 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 2005.

Introduction

Monitoring Network

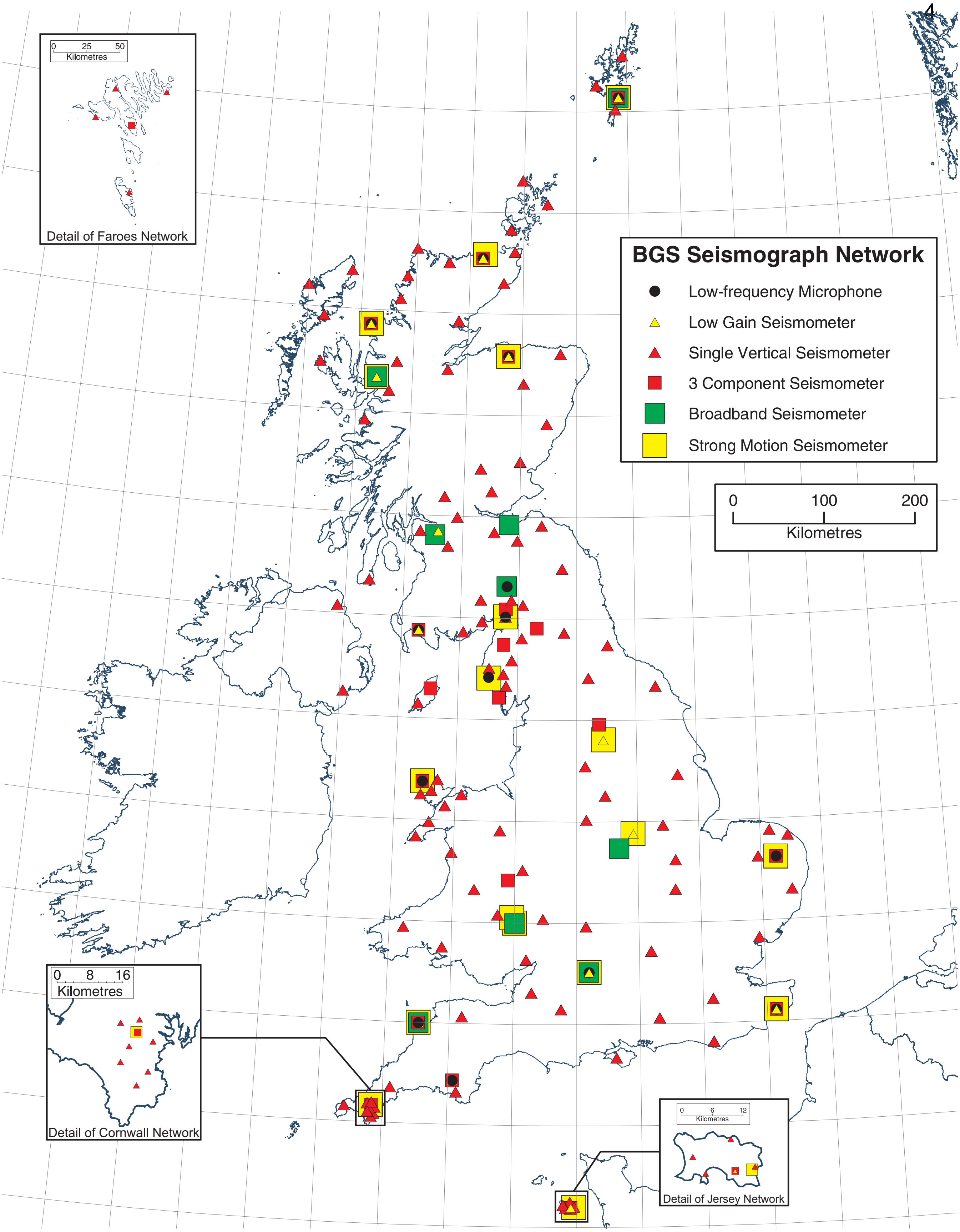
The BGS National Earthquake Monitoring project started in April 1989, building on local networks of seismograph stations, which had been installed previously for various purposes. Over time, the network has grown to 146 stations, with an average spacing of 70 km, giving UK-wide coverage and a detection 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. Since then, the network has grown 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 and the Hot Dry Rock geothermal energy project in Cornwall.

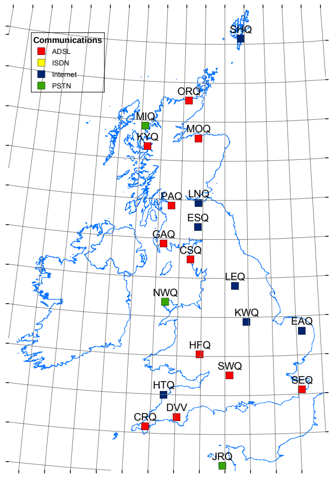
The whole network now consists of a number of sub-networks of up to ten 'outstation' seismometers radio-linked to a central site, where the data are recorded digitally. The system records data continuously, and also creates event-triggered files. Each sub-network is accessed several times a day through Internet or dial-up modems for data transfer to Edinburgh. Once transferred, the events are analysed to provide a rapid response for location and magnitude.

At a number of sites, low-gain vertical seismometers are installed to extend the dynamic range of the system to stronger motions, and low frequency microphones are used to aid the discrimination of sonic booms. In addition, strong motion accelerometers have been installed at locations throughout the country and will remain on-scale for accelerations up to 0.1g.

However, scientific objectives, such as accurately measuring the attenuation of seismic waves, are presently 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. We are now in the process of upgrading our seismograph network. Over the next five years we intend to develop a network of 50-60 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 nine broadband sensors at stations across the UK.



BGS seismograph stations, March 2006.



Communications links to UK seismograph network base stations.

Achievements

Network Development

Broadband sensors with 24-bit acquisition are being deployed to improve the quality of the data by extending the dynamic range and frequency bandwidth of recordings. This will improve the scientific value of the data and improve the services provided to customers.

In the last year three new broadband stations have been installed at: Glennifer Braes (Strathclyde), Plockton (Argyll) and Swindon (Wiltshire). Continuous data from all three stations are transmitted in real-time to Edinburgh, where they are used for analysis and archived.

We have also carried out site surveys for proposed broadband deployments at Yadsworthy (Devon), Haverah Park (Leeds) and the Faroe Isles.

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 Michaelchurch, Herefordshire, 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 network base stations at Orkney and Galloway have been upgraded to use high-speed ADSL connections.

Although all nine 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.

Fourteen new broadband seismometers were purchased during the year 2005-2006. Most of these will be deployed at existing stations as part of our network development program. Some instruments will also be used to improve our rapid deployment capability for studying aftershock sequences and earthquake swarms.




Testing new broadband sensors and digitisers

Near real-time data from short period stations in our Devon, South East England, Lownet and Kyle seismic networks are now being transferred directly to Edinburgh, where they have been 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.

We are now using 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. These modules are independent programs, which use a collection of message passing routines to communicate by broadcasting and receiving various messages such as packets of trace data, phase picks, etc. Standard TCP/IP network broadcasts (UDP) are used to carry messages between computers and shared memory regions within a single computer.

Tasks such as collecting data from a specific piece of hardware at a seismic outstations, archiving the data, event detection and association, all use different modules. The makes the data acquisition very flexible and can carry out numerous different tasks.

Achievements

Information Dissemination

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

Alerts were issued for 18 UK events within the reporting period, one of which was of a suspected sonic origin and one was for the Buncefield explosion, and for 17 global earthquakes. Typically, a bulletin is issued to Customer Group members within two hours of a member of the 24-hour on-call team being notified, and includes earthquake parameters, reports from members of the public, damage and background information. In addition, four enquiries were received from Nuclear Power Stations after alarms triggered, and a response was given within 15 minutes in all cases.

Following the Buncefield explosion of 11 December 2005, which was recorded clearly on stations up to 250 km distance, we were asked to provide information on the origin time of the explosion to the Health and Safety Laboratories (HSL).

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. We have also developed an automatic macroseismic processing system. This was used for the first time following the Fort William earthquake and the Buncefield explosion, allowing rapid processing of macroseismic data and producing macroseismic maps on 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 2005, it was issued within four months.

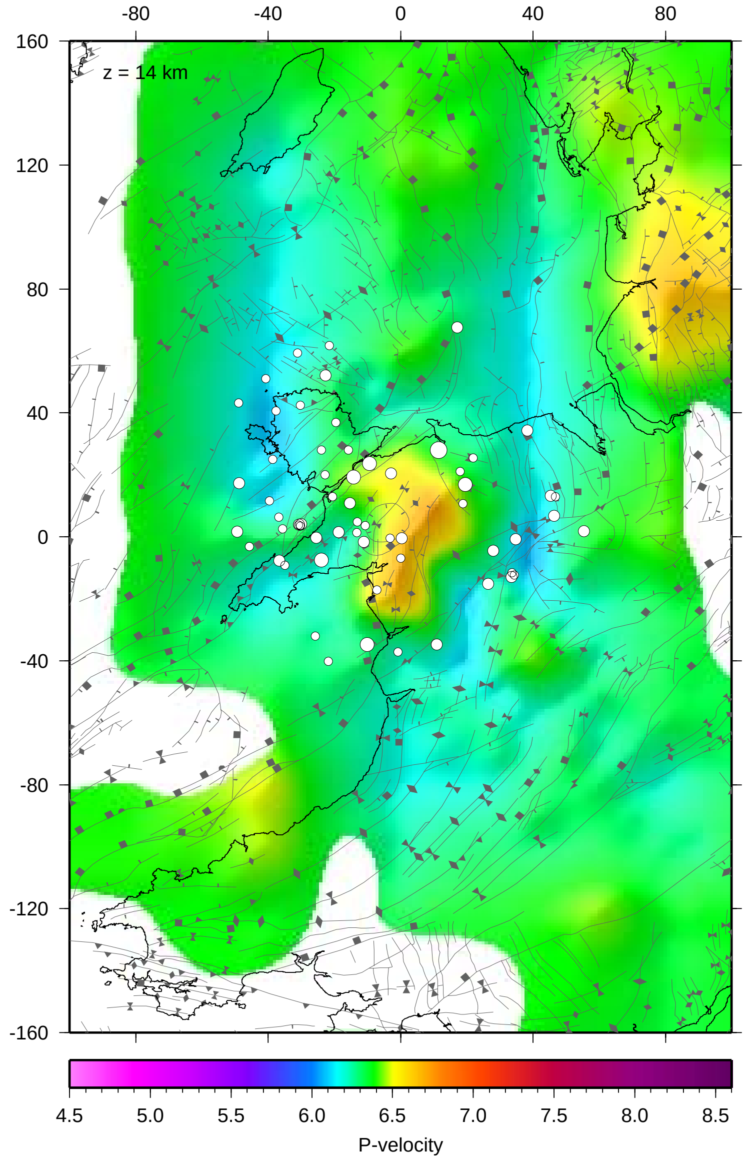
Achievements

Collaboration and Data Exchange

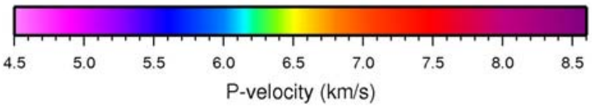
Data from the seismograph network are freely available for academic use and we have continued to collaborate with researchers at academic institutes within the UK throughout the past year, as well as exchange data with European and world agencies.

A continuing project with the University of Leicester, which started in September 2004, is using earthquake data from North Wales recorded on the BGS network to image local variations within the crust of the North Wales region. A three-dimensional model of seismic velocity has been obtained using local earthquake tomography (LET), by simultaneous inversion of seismic travel times and earthquake hypocentres using the method of Thurber (1993). The starting model for LET is a one-dimensional model derived from the joint inversion of *P*- and *S*- arrival times using the procedure of Kissling *et al*. (1994) and represents an estimate of the average crustal velocity for the region.

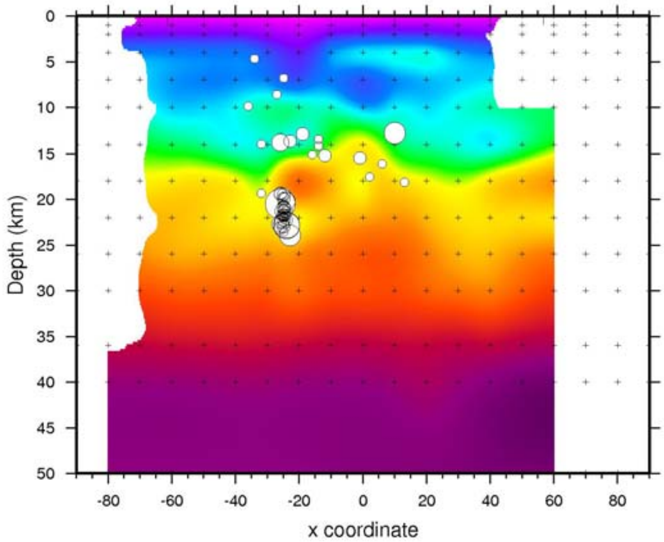
Depth slices and vertical profiles through the resulting 3-D model show variations which can be related to some of the main structural features mapped at the surface. The model highlights a predominantly NE-SW striking structural trend and relocated earthquake foci can be correlated to individual fault populations. In the mid-crust, where the model is best resolved, the Harlech Dome and Snowdonia stand out as areas of anomalously high Vp bounded by significantly lower velocities to the west and east, beyond the Mochras Fault and Conwy Valley fault respectively. In the lower crust a marked E-W velocity gradient is observed on the Lleyn Pennisula in the vicinity of the July 1984 earthquake and aftershock sequence.

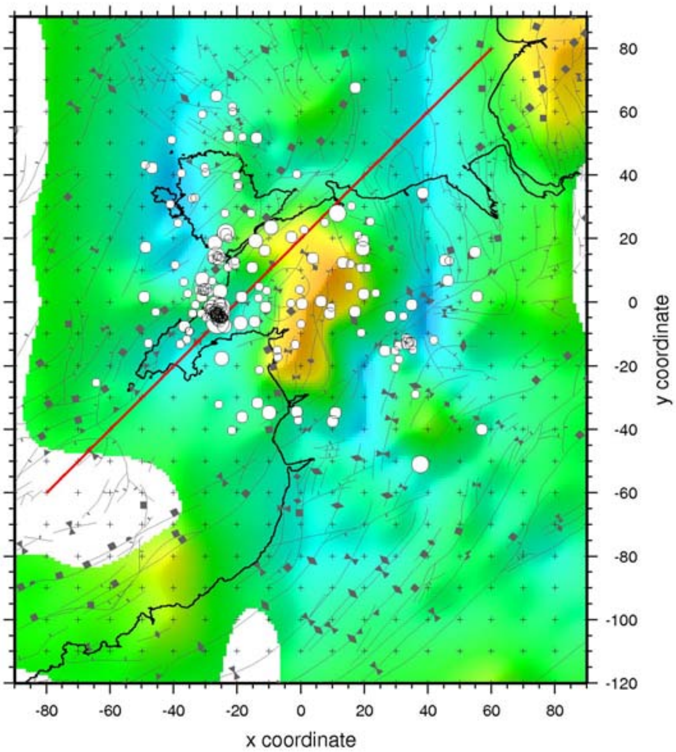


Depth slice through the 3-D velocity model for North Wales at a depth of 14 km



Cross-section along line A-B through the 3-D velocity model for North Wales, along with relocated earthquake hypocentres.



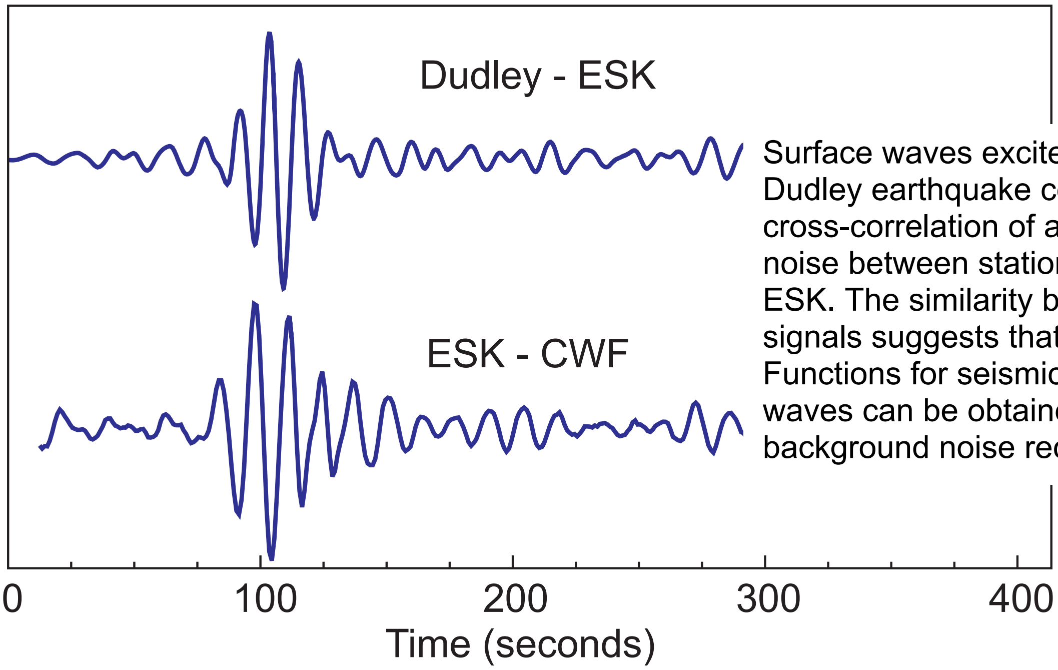


A continuing project with the University of Liverpool and Imperial College London, which also started in September 2004, is using micro-earthquake data collected by the BGS to derive a new attenuation model for Britain. The method of Rietbrock (2001) combines both spectral shape and absolute amplitude information, and uses a tomography style technique to constrain the large trade-offs inherent in conventional approaches.

Synthetic testing and error analysis shows a large reduction in both the absolute errors of inverted parameters, and the sensitivity of the results to the data used. The method has produced a variety of results, including: moment magnitudes, stress-drops, attenuation structure, and the rate of geometrical spreading, along with site-specific responses. Scaling relationships between these parameters have been used to better understand UK seismicity and for future application in seismic hazard applications.

The results will be used to generate synthetic ground motions using the stochastic method of Boore (2003). These synthetic ground motions, expressed as peak ground motion amplitudes and response spectral ordinates, will then be used to derive attenuation relations for the UK, exploring a range of functional forms and fitting techniques. The lower energy P phases will also be used to obtain a finer-resolution attenuation structure, which can be interpreted alongside velocity and geological models to obtain a better understanding of the process of attenuation in the UK.

BGS has hosted two undergraduate projects with students from the University of Edinburgh. The first of these projects involved the application of a new method (Shapiro *et al*, 2005), which uses cross-correlation of continuous background noise recordings to obtain Greens Functions for seismic surface waves propagating between two stations. The second project used cross-correlation and joint location methods to try to improve relative earthquake locations for the North Wales region.



Surface waves excited by the Dudley earthquake compared with cross-correlation of ambient seismic noise between stations CWF and ESK. The similarity between the signals suggests that Green's Functions for seismic surface waves can be obtained from background noise recordings.

BGS has worked with HR Wallingford and the Proudman Oceanographic Laboratory on a study commissioned by the Defra Flood Management Division to assess tsunami hazard for the UK and Irish coast. The main objective of the study was to refine the potential impact of a repeat of the 1755 Lisbon earthquake and tsunami. Fault rupture parameters determined by BGS were used to calculate the vertical uplift of the seafloor for a number of possible scenarios, and provide an input for numerical modelling of the tsunami wave and its impact on the UK. Modelling carried by HR Wallingford and POL gives maximum wave heights of 1-2 m around most of Cornwall, with 3-4 m identified between Penzance and Lizard Point.

INGV, Milan, GFZ, Potsdam, and BGS have worked 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.

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

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. Over the year we have tried to promote our work to as wide an audience as possible, through lectures and presentations, our information booklet, the Internet and media interviews.

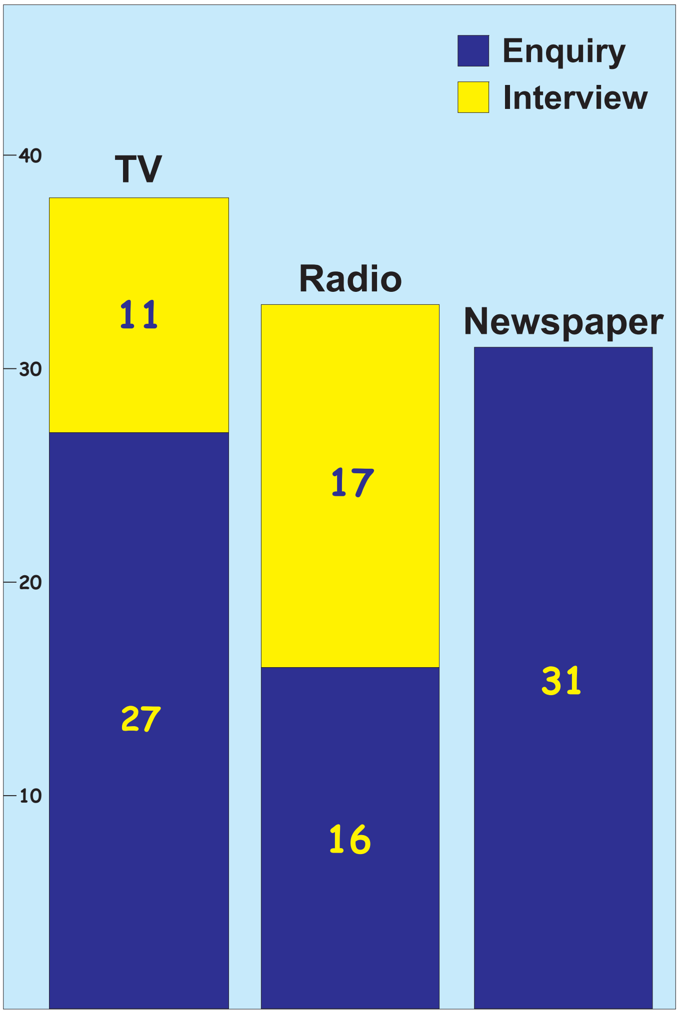
A number of lectures and presentations were given to schools, university students and other interested parties. The BGS Open Day in September attracted 905 visitors with many of them visiting the interactive earthquake display. A further 147 school pupils from 12 different schoolds visited during the following Schools Week.

BGS has 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”. The aims of the project are to co-ordinate and develop UK specific tools and resources for teaching and learning seismology in UK schools. This will help school students conduct real investigations using seismological data collected at schools. School seismometers can provide teachers and students with the excitement of being able to record their own real scientific data, which can be shared online with a global audience of other teachers, pupils and scientists. This project will build on the efforts of a handful of dedicated teachers in the UK who are already experimenting with seismology.

The Seismology web site continues to be widely accessed, with over 330,000 visitors logged in the year. Significant peaks were observed in October, following the Pakistan earthquake (over 7,000 visitors in one day), and December, following the Fort William earthquake and Buncefield explosion.

New look web pages were launched in September 2005. These incoporate real-time data from UK broadband stations and the online macroseismic questionnaire. The most popular pages are the "Recent Events" pages.

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 2005-2006, 469 enquiries were answered. Some 102 of these were from the media, including 71 for TV and radio broadcasts following significant earthquakes. The broadcasting enquiries led to 11 TV and 17 radio interviews.



Seismic Activity

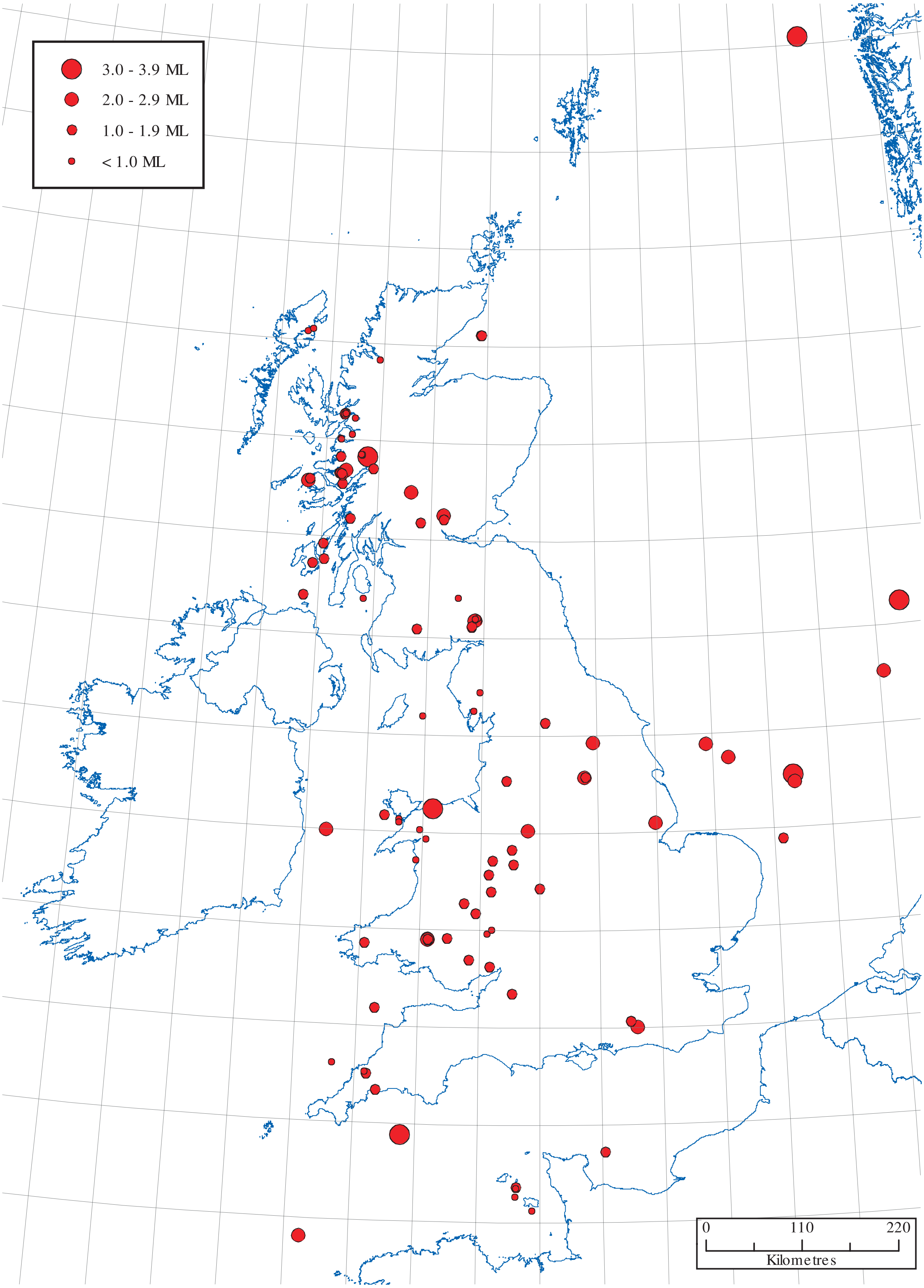
The details of all earthquakes, felt explosions and sonic booms detected by the BGS seismic network have been published in monthly bulletins and compiled in the BGS Annual Bulletin for 2005, published and distributed in April 2006 (Galloway, 2006).

There were 112 earthquakes located by the monitoring network during the year, with 27 of them having magnitudes of 2.0 ML or greater and six having magnitudes of 3.0 ML or greater. Twelve events with a magnitude of 2.0 ML or greater were reported felt, together with a further three smaller ones, bringing the total to fifteen felt earthquakes in 2005.The largest onshore earthquake had a magnitude of 3.3 ML and occurred near Conwy, North Wales, on 14 February 2005. The largest offshore earthquakes occurred in the northern North Sea on 27 June and in the central North Sea on 7 September, both with magnitudes of 3.2 ML. The northern North Sea event was located 270 km east northeast of Lerwick, Shetland Islands and the central North Sea event was located 390 km east of Newcastle upon Tyne.

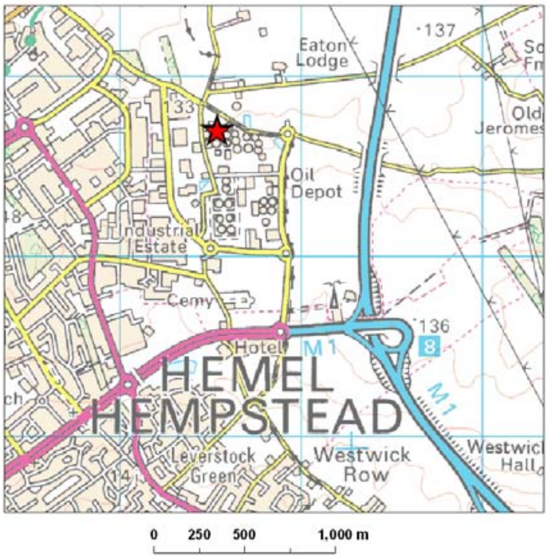
The spatial distribution of seismicity in 2005 generally reflects that observed in the instrumental catalogue as a whole, with the majority of earthquakes occurring in and around Wales, Cornwall, the Midlands, Cumbria and the Scottish Borders and in western Scotland. There was also activity in the northern and southern North Sea. Three events in unusual locations occurred near Billinghurst, W. Sussex, in June and July 2005. The largest had a magnitude of 2.1 ML. A magnitude 2.8 ML earthquake on 14 December 2005 near Wicklow was the first earthquake to be widely felt in Ireland, since the magnitude 5.4 ML Lleyn Peninsula earthquake. It was also the largest Irish earthquake since 1951. Historically, southeast England has been active but Ireland and northeast Scotland have rarely experienced events in the past.

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 2005 to March 2006, a total of 387 teleseismic earthquakes were detected and analysed.

In the following sections, we provide more detailed reports of the magnitude 3.0 ML earthquake near For William, (2005), and our analysis of signals from the Buncefield explosion (2005). We also report on the catastrophic Pakistan earthquake of 8 October 2005.



Epicentres of all UK earthquakes located in 2005.



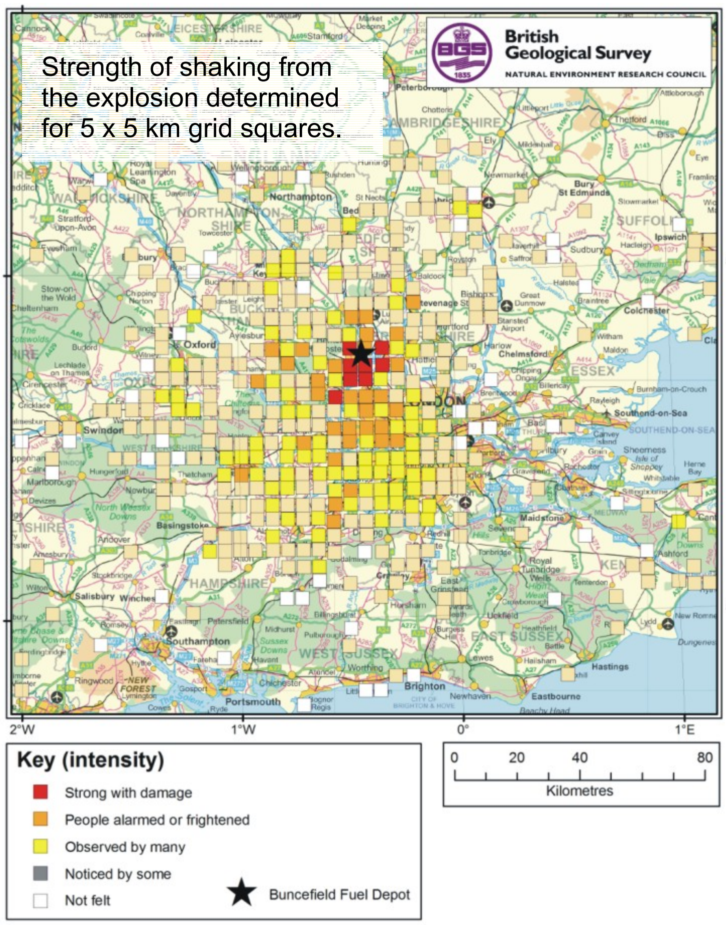
Seismic Activity

Buncefield

A massive explosion on 11 December 2005 at the Buncefield Fuel Depot near Hemel Hempstead started a fire lasting for about two days. Seismic and acoustic waves generated by the explosion were detected on the BGS seismograph network. Accurate timing of the explosion was established from the seismograph recordings in a report commissioned by the Health & Safety Laboratory (Ottemöller, 2006).

The first and main explosion at the Buncefield fuel depot near Hemel Hempstead, just after 06:00 UTC on 11 December 2005 was the largest in peacetime Britain. The explosion was widely recorded at seismic stations throughout England and Wales, and the most northerly recordings were made at Eskdalemuir (Scotland). Outside the UK, the explosion was measured on seismic and infrasound stations in the Netherlands. There were reports of additional smaller explosions that occurred within half an hour of the main explosion. However, these were not detected on the seismic stations, indicating that they were significantly smaller. A cloud of smoke caused by the fire was visible from space. The fire severely affected the surrounding areas and caused disruption to motorways and air traffic.

As the main explosion was widely felt by the public over a wide area, a macroseismic survey was carried out by the BGS. The survey was advertised on the BBC news website resulting in a total of over 3,000 completed questionnaires. The results confirmed that the explosion was felt throughout a large part of England, with the most distant reports coming from as far north as Lancashire, West Yorkshire and Humberside, and as far west as Powys, Mid Glamorgan and Somerset. However, damage was restricted to the vicinity of the explosion site.

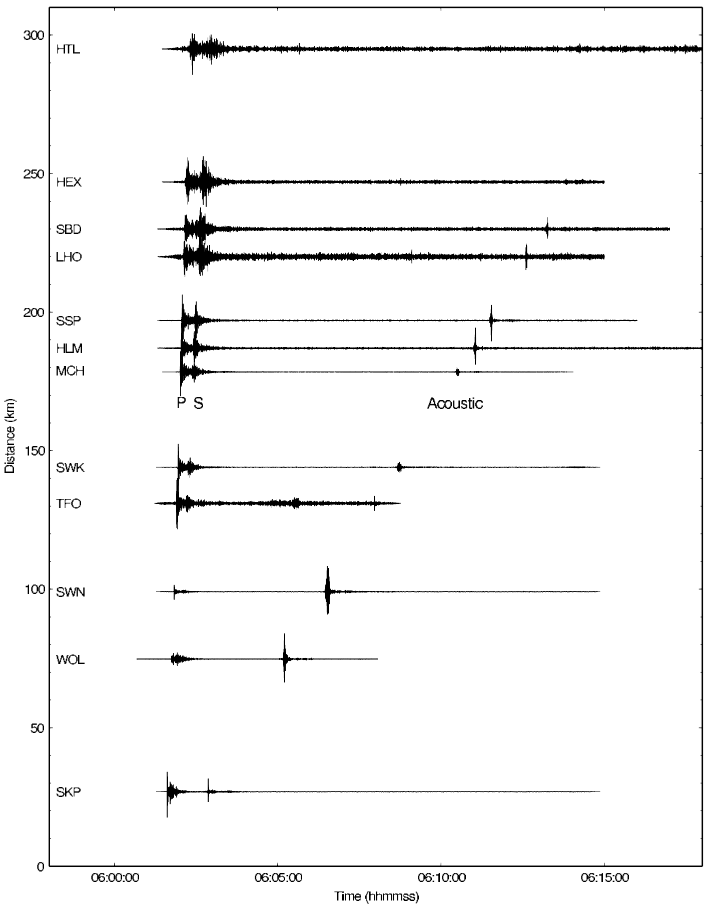


Surface explosions generally release most of their energy into the air as acoustic waves. Several acoustic wave types with distinct travel paths, either direct or refracted within the upper atmosphere, were detected on the seismograph stations from the Buncefield explosion. The speed of sound varies in different directions depending on temperature and pressure, and use of the acoustic wave arrivals to determine the origin time is less certain than using seismic arrivals.

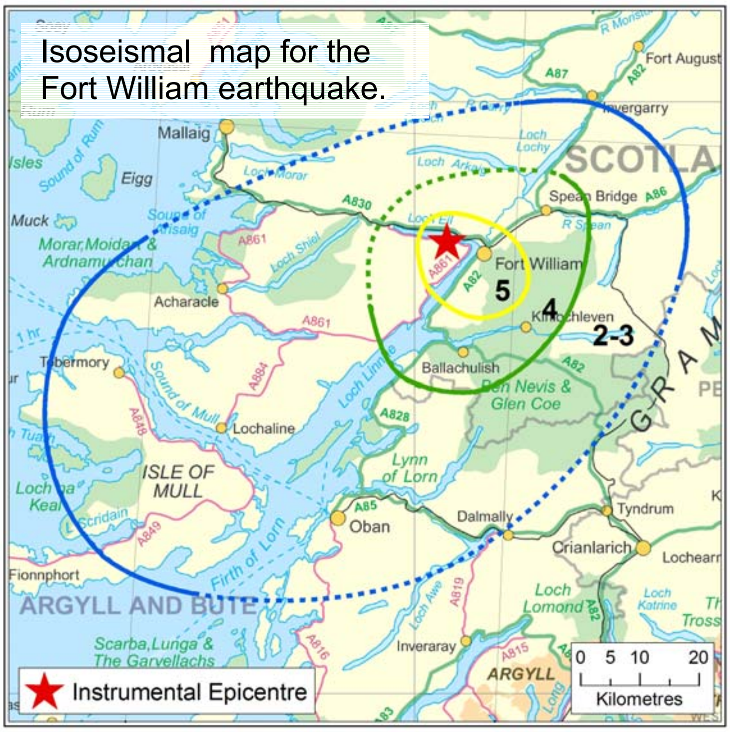
The origin time of the Buncefield explosion determined from a total of 21 seismic P-wave arrivals at distances of up to c. 250 km is 06:01:31.45 UT (±0.5 sec). Location and depth are kept fixed in the calculation, since these are known. The largest residual obtained when inverting for origin time only, is –0.42sec and most of the residuals are larger than the picking error. The residuals are explained by lateral deviation of “true” crustal wave velocities from the layered velocity models that were used. The model that explained the travel times from the explosion best was the model derived for Mid Wales (Edwards and Blundell, 1984). Use of alternative models resulted in slight, but not significant changes. The formal uncertainty of 0.5sec for the origin time can be regarded as a robust maximum.

Explosions with known location and depth can be used to calibrate or validate the earthquake location procedure. To investigate the accuracy of the method and model, the data set was inverted for location and origin time for the fixed depth of 0km. The location obtained through inversion using the Mid Wales model shifted by 1.4km to the northwest, and the origin time increased by 0.1sec. This change in origin time is well within the formal error of 0.5sec and the difference between true and computed location of only 1.4km shows that the Mid Wales model is suitable for this analysis.

The arrival times of the acoustic waves can also be used to determine the origin time. However, the result will have a larger uncertainty. The determined origin time was used to obtain observed and calculated travel times of the direct acoustic wave for verification of the origin time, assuming a sound speed of 334m/s. Due to the inhomogeneous atmospheric conditions, the residuals between the observed and calculated travel times of the direct acoustic waves are relatively large (up to 10sec). However, overall the data is well explained by the origin time and the average sound speed.



Seismograms showing recordings of both seismic and acoustic waves at selected stations, originating from the Buncefield explosion as function of distance. The station codes are given on the left. Arrival times are marked as P, S and Acoustic. Signals are proportional to ground displacement and filtered in the 3-8Hz frequency band.



Isoseismal map for the Fort William earthquake.

Seismic Activity

Fort William

Numerous reports were received from members of the public in and around Fort William on 10 December 2005, following a magnitude 3.0 ML earthquake. An online questionnaire was used to collect macroseismic data. The maximum observed intensity was 5 (EMS).

This earthquake occurred on 10 December 2005 at 23:21 UTC, with an epicentre approximately 8 kilometres west of Fort William. The instrumental magnitude was determined at 3.0 ML, and initial reports suggested that the earthquake had been felt throughout Lochaber. A macroseismic survey was launched on the BGS 'Earthquakes' web site. A total of 210 responses were received.

The highest intensity experienced was 5 EMS, which was observed over an area extending approximately 14 kilometres to the northeast and southeast of the epicentre. Unsurprisingly, the greatest number of replies came from Fort William.

Comments received included descriptions of the noise made by the earthquake as sounding like a heavy clap of thunder, a gust of wind, or even a quarry blast. Most of the people who felt the event described the shaking as weak to moderate. A few people reported objects falling over or coming off their wall fixing. There were no reports of damage to property.

The most distant report was from the south of Mull, 75 km to the southwest. The total felt area is over 7,300 sq km. The areas within each isoseismal (rounded to the nearest 100 km^2) were as follows: 1,100 km^2 (isoseismal 4) and 215 km^2 (isoseismal 5).

Parameters for the earthquake were calculated from these macroseismic data. The magnitude was calculated to be 3.4 ML, slightly higher than the instrumental value. The macroseismic depth is around 6 km, compared to the instrumental determination of 10.8 km. Since both values are subject to an uncertainty of a few km, the figures are consistent with one another.

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Damage in NW Balakot (T.Rossetto, UCL/EEFIT).

Global Earthquakes

The devastating Pakistan earthquake was the most disastrous during 2005, accounting for over 97% of the fatalities. The earthquake caused the deaths of at least 89,000 people, injured more than 75,000 others, left nearly 3 million homeless and caused extensive damage in northern Pakistan, India and Afghanistan.

A magnitude 7.6 Mw earthquake occurred on 8 October at 03:50 UTC in northern Pakistan The heaviest damaged occurred in the Muzzaffarabad area, Kashmir, where entire villages were destroyed, and in Uri where nearly 80% of the town was destroyed. Around 32,000 buildings collapsed in Anantnag, Baramula, Jammu and Srinagar, Kashmir and many other buildings also collapsed in Abbottabad, Gujranwala, Gujrat, Islamabad and Lahore, Pakistan. Landslides and rockfalls destroyed or damaged many mountain roads and highways cutting off access to the region for several days. Landslides were also reported from the towns of Gilgit and Skardu in Kashmir, and liquefaction occurred in the western region of the Vale of Kashmir. Seiches were observed in Haryana, Uttar Pradesh and West Bengal, India and in many places in Bangladesh.

Compared to the more seismically active area of the Hindu Kush mountains of Afghanistan, approximately 350 km to the northwest, the mountainous region 90 km to the north of Islamabad does not generally experience many earthquakes above magnitude 6.0. Historically, there have only ever been three such events recorded in this small region; the largest being a magnitude 7.3 in 1937, followed, in size, by a 6.8 in 1928, and then a 6.3 in 1974 (which caused the deaths of 900 people). Since 1973, the number of earthquakes with a magnitude of between 5.0 and 6.0 amounts to only 5.

This earthquake occurred as a result of the collision of the Indian sub-continent with Eurasia. India is moving north at a rate of around 4 cm/year. The collision causes compression and uplift, forming the Himalaya, Karakoram and Hindu Kush mountain ranges. Compression is also accommodated by slip on a number of major thrust fault zones, resulting in earthquakes over a wide area along the collision zone. The earthquake on 8 October probably occurred on one of these thrust faults. Large destructive earthquakes have struck Kashmir in the past. In 1905, an earthquake on the Kashmir-India border region killed 19,000 people. More recently, a magnitude 6.3 earthquake in 1981 in northwest Kashmir killed over 200 people. Pakistan’s previously most damaging earthquake occurred near the city of Quetta in 1935, killing 30,000 people.

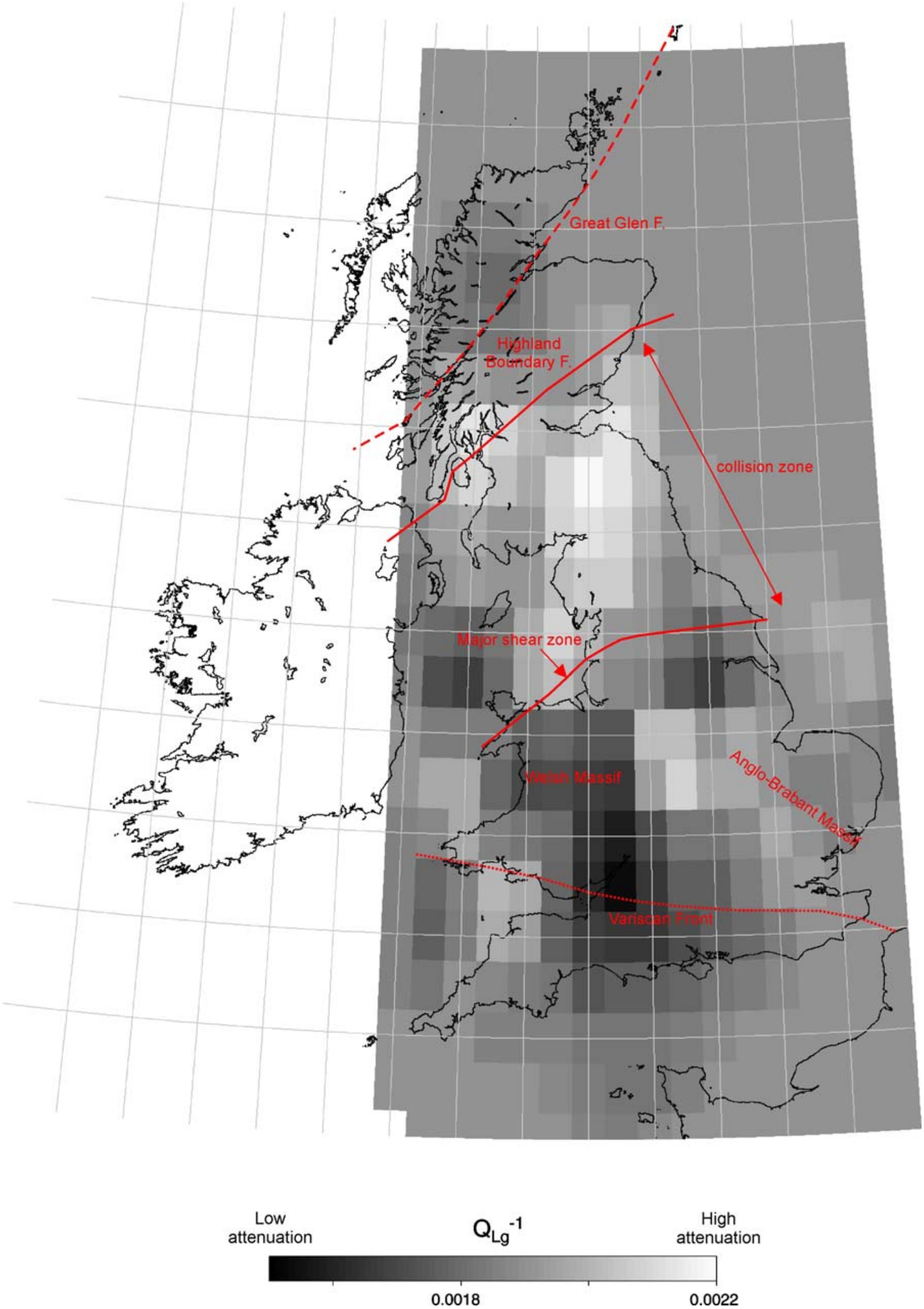
Scientific Objectives

Lg-wave Attenuation

The strength of *Lg* wave attenuation strongly correlates with geology. As a result, lateral variations in the strength of *Lg* wave attenuation can be used to map large-scale features of the crust in the UK.

The highly complex evolution of the UK is reflected in the intricate jigsaw of tectonic terranes (fault bounded areas characterised by a structure and history distinct from those of adjacent areas) that exists today. Identifying individual terranes from geological mapping is somewhat problematic because of the lack of consensus regarding which structures constitute terrane boundaries. There is also the additional uncertainty as to whether boundaries mapped at the surface persist at depth.

By analysing Lg wave attenuation using a dataset comprising over 500 seismograms, it has been possible to detect several of the main terranes/terrane boundaries in the UK. Lg waves are S-waves that are multiply reflected and trapped in the crust, and are usually observed on seismograms out to distances of several thousand kilometres. The results seem to be consistent with the hypothesis that the Great Glen Fault is not a terrane boundary, despite being a major fault system, since there does not appear to be any variation in attenuation across this structure (although this is not particularly well resolved). The Highland Boundary Fault (which coincides with the transition from relatively low/average attenuation in the older terranes of northern Scotland to higher than average attenuation to the south) is a known boundary that delineates the northern edge of the collision zone associated with the closure of the ancient ocean Iapetus. A wide shear zone that runs through Anglesey and northern England marks its southern edge. The whole of this region is imaged as a zone of relatively high attenuation. Further south, the picture becomes more complex but it appears that the Welsh Massif is associated with lower than average attenuation whilst the younger Anglo-Brabant Massif region is characterised by relatively high attenuation. No indication of the northern edge of Variscan deformation is detected but this may be due to the limited resolving power of the data in southernmost England.



Results of the tomographic inversion for attenuation of *Lg*-waves. The lighter shading shows areas of low attenuation, as seen across the Midland Valley of Scotland.

Scientific Objectives

What controls the location of British earthquakes?

The spatial distribution of earthquakes in the British Isles is not random. But the reason why earthquakes are clustered in some parts of the UK and not in others has always been a puzzle. We have recently reviewed the various theories that have been put forward.

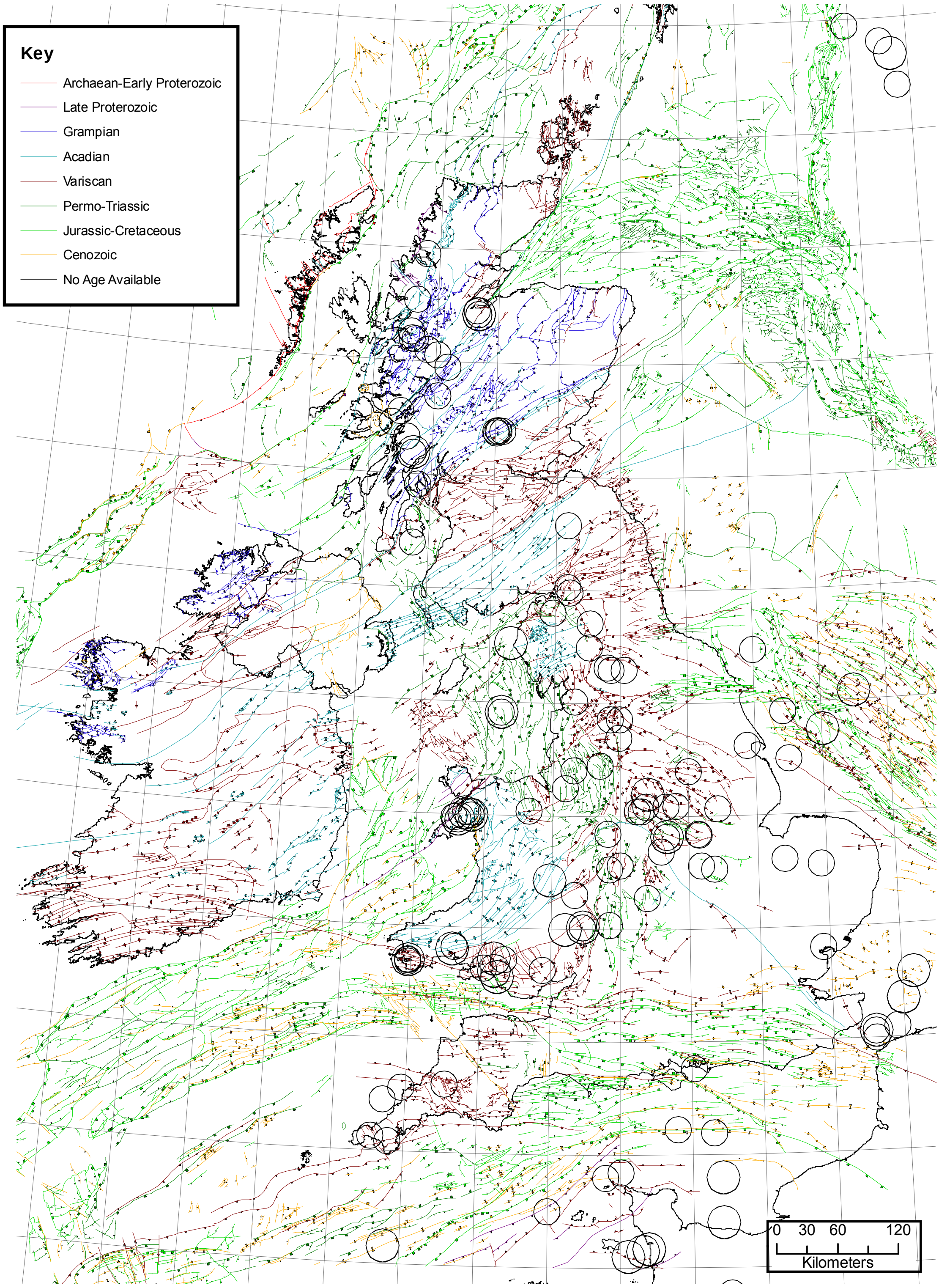
Comparing a map of British seismicity with a geological or structural map poses problems. Earthquakes are relatively common in some parts of the country and totally missing from others, and there is no obvious geological explanation. Theories that have been put forward to explain this can be grouped into the following categories: influence of recent tectonic evolution; patterns controlled by deglaciation and isostatic recovery; conjunction of seismicity and zones of major faulting; distribution controlled by upper mantle processes; and patterns of stress interaction.

Most of these suffer from the problem that it is difficult to demonstrate that earthquake activity is controlled by a given factor, and that there are always some mismatches.

An example is the association of earthquakes with zones of major faulting. “Corridors” along the line of major faults in the UK take in most large earthquakes. However, to say that earthquakes are equally likely anywhere along these fault corridors is another matter. Large areas appear to be “suitable” for earthquakes yet remain aseismic.

A promising line of approach is that of stress patterns and the geometry of the crustal blocks that make up the British Isles. The shape of different structural units determines how they interact when subjected to regional compression. For example, the northward angular point of the Midlands microcraton means it can act somewhat as an indenter under compression from the northwest, but with more seismicity both expected and observed on the western side than the “protected” eastern side. If the microcraton had a different shape it would interact differently. Aseismic areas may be effectively in the stress shadow of sequences of blocks that are absorbing regional stress.

Ideally a model should be such that one could predict the distribution of seismicity without actually knowing it. In practice this is not likely to be possible because there are too many unknowns. However, this geometric approach to structural interaction does open up the possibility of a kinematic model of UK seismogenesis that should improve future estimates of seismic hazard.



Historical and instrumental earthquakes, ML ≥ 4.0, superimposed on a tectonic fault map of the UK.

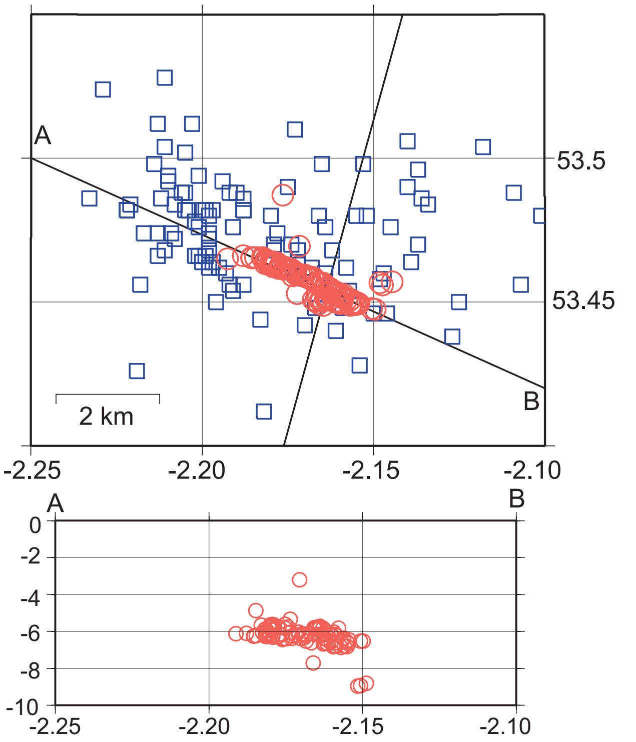
Improving Earthquake Locations

Several recent studies have demonstrated that precise relative earthquake locations can be obtained by using a double difference location algorithm with a combination of catalogue and cross-correlated phase readings. Such studies are generally undertaken in areas of high seismicity. We have investigated how these techniques can be applied to the UK, a low seismicity area, and found that significant improvements can be achieved.

While the distribution of earthquakes in the UK is mostly diffuse, earthquakes also reoccur in the same location separated in time by seconds to years. The Aberfoyle earthquake sequence of 2003 is an example, with 11 earthquakes separated by less than 1km over a 3 months period. Earthquakes that occur in nearly the same location are likely to be associated with the same fault structures, and produce near identical differences in arrival times between different station pairs. Under ideal circumstances inversion of travel time data should result in identical locations. However, manual picking of phase arrivals results in small errors that causes events from the same locations to be located some distance apart.

For events with nearly identical waveforms, it is more precise to determine relative travel times between event pairs using waveform cross-correlation. The time corresponding to the maximum correlation gives the relative time difference between two events recorded on one station. We cross-correlated pairs of events recorded since 1995 that were less than 30km apart. Data windows were extracted based on the catalogue location and computed arrival times. A band-pass filter was applied before computing cross-correlation. Events that are correlated belong to the same family and share location and source mechanism. The outcome from this is a data set of precise relative arrival times.

This data-set was then used together with the catalogue arrival times as input to the double-difference location method of Waldhauser (2001). This method minimizes the difference between the travel time residuals of earthquake pairs, which practically means that the preferred solution is to have the two earthquakes close together. Since the velocities along a path for neighbouring earthquakes recorded on one station are nearly identical, no station- or source-specific corrections are required. The method allows combination of catalogue readings with precise relative travel time differences obtained through waveform correlation. The absolute locations are determined by the catalogue data, while the relative locations are determined by precise travel time differences.

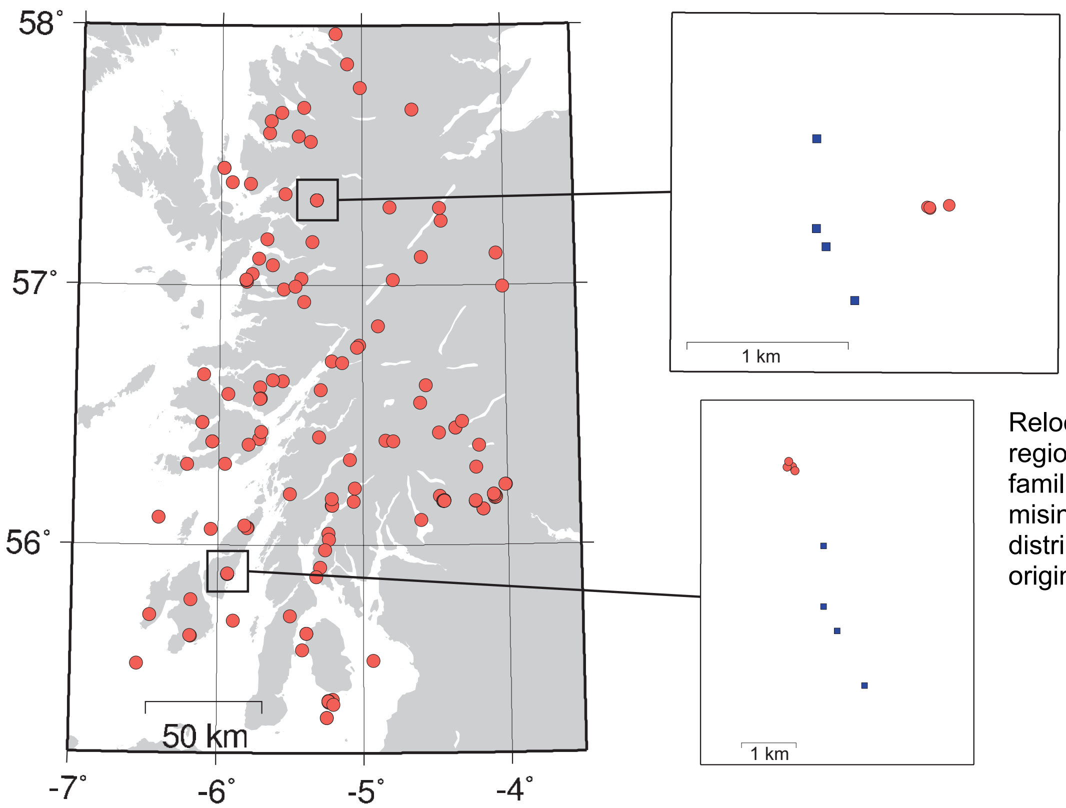


Catalogue (blue) and relocated (red) hypocentres from the Manchester earthquake swarm, 2002.

Significant improvements in relative earthquake locations were achieved for the Manchester earthquake swarm in 2002 and the Aberfoyle earthquake sequence in 2003. In both cases, the very diffuse distribution seen in the catalogue locations sharpens significantly with seismicity falling onto a single line. Applying these methods to the aftershocks of the 1984 Lleyn Peninsula earthquake (5.4ML) was hampered by clipped recordings of the aftershocks. However, some improvement was achieved by relocating the catalogue data using the double difference method.

Clustering of earthquakes on a small scale was also resolved in a number of locations in Scotland and Wales. The cluster size of event families was reduced from a few kilometres in the single event catalogue to some tens of metres after applying cross-correlation and double difference location. Correct identification of these event clusters and improved location prevents misidentification of apparent fault lines as possibly suggested by catalogue locations.

Compared to other regions of high seismicity where these techniques help to sharpen the image of large fault systems, improvement of relative locations in the UK is on a much smaller scale. The two main applications in the UK are: 1) to sharpen the earthquake distribution of swarms or aftershock sequences, which allows us to identify single causative faults; 2) to identify small event families and to remove apparent linear distribution, which may otherwise lead to false tectonic interpretation.



Relocated hypocentres (red) in two regions of Scotland identify event families, which could otherwise be misinterpreted as linear distributions of events from the original catalogue locations (blue)

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

BGS Seismic Monitoring and Information Service

Brian Baptie	Project Leader

Research

Roger Musson	Seismic Hazard
Lars Ottemoller	UK & Regional Seismicity
Susanne Sargeant	Seismic Hazard
David Booth	Crustal Structure
Aoife O'Mongain	Crustal Structure

Analysis Team

Glenn Ford	Seismologist
Davie Galloway	Seismologist
Bennett Simpson	Seismologist
Julian Bukits	Seismologist

Technical Operations

John Laughlin	Senior Electronics
Tom Alexander	Field Engineer
Heiko Buxel	Field Engineer
Daniel Dawes	Field Engineer
Willie Velzian	Electronics Engineer

Computing Support

Simon Flower	Senior Software Engineer
Dave Scott	Software Engineer

Consultants

David Kerridge	Programme Leader
Margaret Milne	Programme Secretary

Appendix 2 Publications

BGS Internal Reports

Baptie, B. 2005. Earthquake Monitoring 2003/2004, BGS Seismic Monitoring and Information Service, Sixteenth Annual Report, BGS Internal Report IR/04/94.

Galloway, D.A., 2006. Bulletin of British earthquakes 2005, BGS Report CR/04/074N.

Ottemöller, L. 2006. Timing of the Explosion at the Buncefield Fuel Depot, 11 December 2005. British Geological Survey, Commissioned Report, CR/06/038.

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

External Publications

Musson, R.M.W., 2004. Early seismicity of the Scottish Border region, Annals of Geophysics, vol 47 no 6, pp 1827-1848.

Musson, R.M.W., 2005. Earthquake engineering on the Internet: Earthquake catalogues, SECED Newsletter, vol 18 no 3, pp 10-11.

Musson, R.M.W., 2005. Assessing earthquake risk, Earthwise, no 22, pp 24-25.

Musson, R.M.W., 2005. Against fractiles, Earthquake Spectra, vol 21 no 3, pp 887-891.

Musson, R.M.W., 2005. Comment by R.M.W. Musson on “Comparison between probabilistic seismic hazard analysis and flood frequency analysis”, Eos, vol 86 no 39, p354.

Musson, R.M.W., Toro, G.R., Coppersmith, K.J., Bommer, J.J., Deichmann, N., Bungum, H., Cotton, F., Scherbaum, F., Slejko, D. and Abrahamson, N.A., 2005. Evaluating hazard results for Switzerland and how not to do it: A discussion of “Problems in the application of the SSHAC probability method for assessing earthquake hazards at Swiss nuclear power plants” by J-U. Klügel, Engineering Geology, vol 82 no 1, pp 43-55.

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Ottemoller, L., Nielsen, H.H., Atakan, K., Braunmiller, J. and Haskov, J., 2004. The May 7, 2001 induced seismic event in the Ekofisk oil-field, North Sea. Journal of Geophysical Research, vol 110, B10301.

Ottemöller, L., Seismology at the BGS: an overview, 36th Nordic Seismolgy Seminar, Copenhagen, Denmark, 2005.

Sørensen M. B., L. Ottemöller, J. Havskov, K. Atakan, B. Hellevang and R. B. Pedersen, Tectonic processes in the Jan Mayen Fracture Zone based on earthquake occurrence and bathymetry, EGU, Vienna, 2005.

Ottemöller L., Improvement of earthquake location in the UK using correlation techniques, IASPEI meeting, Santiago, Chile, 2005.

Appendix 3 Publication Summaries

Earthquake Monitoring 2005/2006, BGS Seismic Monitoring and Information Service, Sixteenth Annual Report

B. Baptie, B.

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 British Geological Survey (BGS) has been charged with the task of operating and further developing a uniform network of seismograph stations throughout the UK in order to acquire standardised data on a long-term basis. The project is supported by a group of organisations under the chairmanship of the Office of the Deputy Prime Minister (ODPM) with major financial input from the Natural Environment Research Council (NERC).

In the 15th year of the project four new broadband seismograph stations were established, with strong-motion accelerometers deployed at three of these sites. A further four stations were upgraded to high dynamic range data acquisition. All except one of the seismic sub-networks now use data loggers running under the QNX operating system. Ten portable data loggers were purchased, which can be rapidly deployed to record data from aftershock sequences and earthquake swarms and to study specific areas.

All significant felt events and some others 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, following revision, were compiled into an annual bulletin (Simpson, 2004). In all reporting areas, scheduled targets have been met or surpassed.

A Bulletin of British Earthquakes 2005.

D.A. Galloway (ed)

The British Geological Survey's (BGS) Seismic Monitoring and Information Service operates a nationwide network of seismograph stations in the United Kingdom (UK). The whole of the UK, including coastal waters, is covered within the limits of the detection capabilities of the seismograph network. Location accuracy is extended in offshore areas through data exchange with neighbouring countries. Seismic phase data, location details and magnitudes are presented in this Bulletin for all earthquakes detected and located by BGS during 2005 in Tables 1 and 2, together with maps showing the larger magnitude events since 1979 (ML> 2.5) and since 1970 (ML> 3.5). The bulletin covers all of the UK land mass and its coastal waters including the North Sea to 800 kmE and 1500 kmN.

Early seismicity of the Scottish Border region

RMW Musson

This paper considers the seismicity of southern Scotland and northern England up to the year 1750. This area was formerly a border area between two states that eventually became politically united. Much of the area is uplands, and the seismicity is moderate to low. This makes for some problems in studying historical seismicity, yet the area provides a number of interesting case studies of general interest in the field of historical seismology, including a rare case of being able to track down a “missing” earthquake.

Earthquake engineering on the Internet: Earthquake catalogues

RMW Musson

In the first article of this series about Internet resources for engineering seismology, on strong-motion data, Bommer and Strasser (2004) surveyed the main Internet sites from which users can download accelerograms. While the situation is now rather good for those who need to access strong-motion data online, it is not nearly so good with regard to those interested in obtaining earthquake catalogues that might form the starting point for a seismic hazard study. It is not so much that online earthquake catalogues cannot be found – there are many; the problem is rather that the pitfalls for the unwary user of such files are numerous.

The great difference between strong-motion data and earthquake catalogues is that, while an accelerogram is data, in the sense of information acquired directly from nature, an earthquake catalogue is an artifice of interpretation. We may speak loosely of a list of earthquakes as seismicity data, but it is highly processed from the actual raw material, which might be seismograms or macroseismic data. How well the catalogue reflects reality may be far from discernable to the student who simply downloads the numbers from an Internet site and begins to process them. While it is something of a truism to remark that quality control is something often lacking in Internet sites, it has to be borne in mind that, of all the types of information one may need to process in earthquake engineering and seismology, the parametric earthquake catalogue is probably the most subject to fantasy and error. Yet exaggerated and false catalogue entries can be quite difficult to detect. The Internet earthquake catalogue is truly a case of caveat lector.

Assessing earthquake risk

RMW Musson

Many years ago it was thought by most people that one day the threat to society from earthquakes would be solved, or at least mitigated, through earthquake prediction. If one knew in advance where and when a major earthquake was about to strike, appropriate defence measures could be taken to ensure that loss of life was kept to a minimum. In practice, despite enormous efforts, no consistent way of predicting earthquakes has ever been found, and there is a growing belief that earthquakes may be inherently unpredictable, at least with regard to the sort of prediction that could be exploited for civil defence. At present it seems that the best way to defend against earthquakes is through engineering solutions. The need for knowing when an earthquake will happen is removed. Whenever the earthquake occurs, people will be safe because their built environment is earthquake-resistant.

One of the fascinations of seismic hazard analysis is the way in which so many different types of information are distilled together. The earthquake catalogue draws not only upon the skills of the seismologist but often also the historian and even the archaeologist. The work of the geologist, the geophysicist and the geodesist are drawn together in piecing together the pattern of seismogenesis. Seismic hazard really benefits from a truly multidisciplinary approach, in which, by amalgamating expertise across the earth sciences, we can more effectively understand and quantify the hazard from earthquakes worldwide.

Against fractiles

RMW Musson

This paper discusses the proposal to replace the use of mean hazard curves for engineering design with curves based on some fractile drawn from a logic tree, such as the 84% value. Such a proposal breaks with the principle of probabilism. If one wishes to know the hazard value that has a certain return period, by definition this is the mean hazard value and no other. Fractile curves are unhelpful. They represent what the hazard would be if a certain combination of parametric values were known to be true. In practice this is never the case because of the extent of epistemic uncertainty. The proposal to introduce the use of fractile curves seems to be motivated by a dislike of the fact that at very long return periods, the mean hazard becomes controlled by extreme values within the model. This is a fact of life, and the solution is either to exert more care in model design, or not attempt to use values with extremely long return periods, which necessarily approximate to worst case scenarios.

Comment by R.M.W. Musson on “Comparison between probabilistic seismic hazard analysis and flood frequency analysis”

RMW Musson

A paper by Wang and Ormsbee is shown to repeat a number of errors from a previous paper by the same authors, despite it having been shown in the mean time that the arguments in question are false. These errors include misinterpretation of probability theory and the use of obsolete citations.

Evaluating hazard results for Switzerland and how not to do it: A discussion of “Problems in the application of the SSHAC probability method for assessing earthquake hazards at Swiss nuclear power plants” by J-U. Klügel

RMW Musson, GR Toro, KJ Coppersmith, JJ Bommer, N Deichmann, H Bungum, F Cotton, F Scherbaum, D Slejko and NA Abrahamson

The PEGASOS project was a major international seismic hazard study, one of the largest ever conducted anywhere in the world, to assess seismic hazard at four nuclear power plant sites in Switzerland. Before the report of this project has become publicly available, a paper attacking both methodology and results has appeared. Since the general scientific readership may have difficulty in assessing this attack in the absence of the report being attacked, we supply a response in the present paper. The bulk of the attack, besides some misconceived arguments about the role of uncertainties in seismic hazard analysis, is carried by some exercises that purport to be validation exercises. In practice, they are no such thing; they are merely independent sets of hazard calculations based on varying assumptions and procedures, often rather questionable, which come up with various different answers which have no particular significance.

The seismicity of Wales

RMW Musson

Wales is one of the more seismically active parts of the UK, but the pattern of seismicity in Wales is quite varied. There is a small area in NW Wales that is highly seismic, and includes some of the largest British earthquakes. The largest onshore British earthquake occurred SW of Caernarfon. The rest of N Wales is only moderately active in comparison. Mid Wales is much quieter, while South Wales is again an active zone. Thus within Wales, seismicity is not evenly distributed, and the larger earthquakes have occurred in NW Wales and S Wales only. Any geological explanations for this distribution are speculative. Seismicity in S Wales shows an overbalance of earthquake with magnitudes around 5 compared to the number of smaller events, and it seems as if this may be a characteristic magnitude. The larger earthquakes tend to have relatively deep focus: more than 15 km.

Occasionally intensity 7 EMS has occurred in single places, with moderate damage to buildings, but mostly the maximum intensity has been 6 EMS (slight damage) in the higher seismicity areas and 5 EMS (strong) everywhere else. The intensity likely to be observed or exceeded with 10% chance in 50 years is 5 EMS for most of Wales, and 6 EMS around Caernarfon-Bangor and in S Wales. The likelihood of earthquake fault rupture at surface anywhere in Wales is almost zero.

The May 7, 2001 Induced Seismic Event In The Ekofisk Oil-Field, North Sea

L. Ottemöller, H.H. Nielsen, K. Atakan, J. Braunmiller and J. Havskov

A moderate size seismic event on May 7, 2001 was strongly felt on platforms in the Ekofisk oil field, located in the Norwegian sector of the southern North Sea, without causing damage to platforms or wells. We combined observations from the near and far-field to develop a source model and to determine whether the event was induced. Seismic data showed that the epicentre was within the Ekofisk field and suggested a shallow source depth based on spectral and moment tensor analysis. GPS data from the Ekofisk platforms displayed permanent vertical and horizontal movement associated with the event. A bulge of the sea bottom, seen in differential bathymetry data, and overpressure in the overburden in the north-eastern part of the field, which were detected only after the event, had been caused by unintentional water injection that started in 1999. This leakage into the overburden from a single abnormal well was not discovered at the surface due to a cement plug in the annulus of this well. The injection pressure and rate were sufficient to jack up the overburden. Pressure gauge and compaction data ruled out the reservoir as source of the seismic event, further supported by unchanged production rate and absence of well failure during the event. We, therefore, conclude that the event occurred in the overburden, at a depth of less than 3km, although due to very low shear strength of the clay-rich shale and mud rocks this initially appeared unlikely. Our results show that the seismic event was induced due to stress changes caused by water injection. The event possibly initiated on the northern flank and may have involved sudden compaction in the rest of the field. Near-horizontal slip, determined from moment tensor inversion, was the more likely source mechanism, however, alternatively slip may have occurred on a near-vertical plane. Stress drop was low and due to the low overburden shear strength, the event released less energy than a normal stress drop event with similar source dimensions.

Timing of the Explosion at the Buncefield Fuel Depot, 11 December 2005

L. Ottemoller

The main explosion at the Buncefield fuel depot on 11 December 2005 was detected at more than 30 seismic stations in the UK operated by the British Geological Survey (BGS). Smaller explosions reported to have occurred after the main explosion were not detected at the seismic stations, indicating that these were significantly smaller than the main explosion. The BGS seismic stations acquire data at a high sampling rate and with accurate timing and so the data can be used to determine the origin time of the explosion. We analysed the seismograms to identify P-wave arrival times and then used these to compute the origin time. The explosion source location and depth in this procedure were fixed to the known location of the fuel depot. The origin time was determined to have been 06:01:31.45 UTC with a robust uncertainty of 0.5sec. This result was obtained based on a velocity model derived for Mid Wales, in the absence of a specific model for central England. However, the Mid Wales model provides a good match between observed and calculated travel times. Inversion for location, in addition to origin time, resulted in a shift of only 1.4km from the known location and a shift in origin time of 0.1sec. The origin time was also found to be consistent with the arrival times of the acoustic waves that were observed on the seismograms.

Seismology at the BGS: an overview

L. Ottemoller

The British Geological Survey operates a nationwide network of 145 seismograph stations in the United Kingdom. The network is subdivided into twenty regional sub-networks consisting of a number of remote outstations and a central data acquisition and recording facility. Most of these stations are equipped with short-period seismometers. However, it is planned to upgrade the existing network to broadband sensors with high dynamic range digitisation and real-time communications links. At present, 8 broadband stations are in operation. The talk aims to give an overview of existing monitoring equipment and future upgrade plans, including hardware at the remote sites and processing software. About 200 earthquakes are recorded in the UK per year. The talk will also present issues related to the routine analysis and give an overview of current research topics.

Improvement Of Earthquake Location In The UK Using Correlation Techniques

L. Ottemöller

Several earthquake sequences over recent years in the UK showed a high degree in waveform similarity explained by the proximity of individual events that share a similar mechanism. The sequences consist of between a few and hundreds of events. Cross correlation techniques were used to identify families of similar events and then to identify consistent arrival times. Relative event locations within the sequences were improved significantly. The same techniques were applied to a countrywide data set. Preliminary results show that groups of events can be identified. The aim is to sharpen the image of seismicity distribution, which based on standard techniques is rather diffuse, and to improve the seismotectonic understanding. The improved event locations can be used as input for tomographic studies, which will help to improve the crustal velocity models.

Tectonic processes in the Jan Mayen Fracture Zone based on earthquake occurrence and bathymetry

M. B. Sørensen, L. Ottemöller, J. Havskov, K. Atakan, B. Hellevang and R. B. Pedersen

Jan Mayen is a small volcanic island situated along the mid-Atlantic Ridge. It is closely connected with the geodynamic processes associated with the interaction between the Jan Mayen Fracture Zone (JMFZ) and the slowly spreading Kolbeinsey and Mohns Ridges. In spite of the significant tectonic activity expressed by the frequent occurrence of medium to large earthquakes, detailed correlation between individual events and the causative faults along the JMFZ has been lacking. Recently acquired detailed bathymetric data in the vicinity of Jan Mayen has allowed us to document such correlation for the first time. The earthquake of April 14, 2004 (Mw=6), which occurred along the JMFZ, has been studied in detail and correlated with the bathymetry. Interactions between various fault systems are demonstrated through aftershock locations. This gives an insight into the processes occurring along the divergent plate boundary in the North Atlantic associated with the interaction between the JMFZ and sea-floor spreading along the Mohns Ridge.