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NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Earthquake Monitoring 2004/2005

BGS Seismic Monitoring and Information Service

Sixteenth Annual Report

BRITISH GEOLOGICAL SURVEY

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UK Earthquake Monitoring 2004/2005

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Summary

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) operates a 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 16th year of the project two new broadband seismograph stations were established, two strong-motion accelerometers were installed at Sellafield, and a further station was upgraded to high dynamic range data acquisition. Almost 75% of the network now uses high-speed communications links that allow continuous data to be transferred in near real-time to Edinburgh. New base stations were established for the Cumbria and Galloway networks. A relational database of all station information is improving the everyday running of the seismic network. Storage and archival capability have been increased and we now have 70 Terra-bytes of online storage and 80 Terra-bytes of tape archive storage for large volumes of continuous seismic data.

All significant events were reported rapidly to the Customer Group through seismic alerts sent by e-mail. The alerts were also published on the Internet (http://www.earthquakes.bgs.ac.uk). Monthly seismic bulletins were issued six weeks in arrears and compiled in a finalized annual bulletin (Simpson, 2005). In all reporting areas, scheduled targets have been met or surpassed.

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

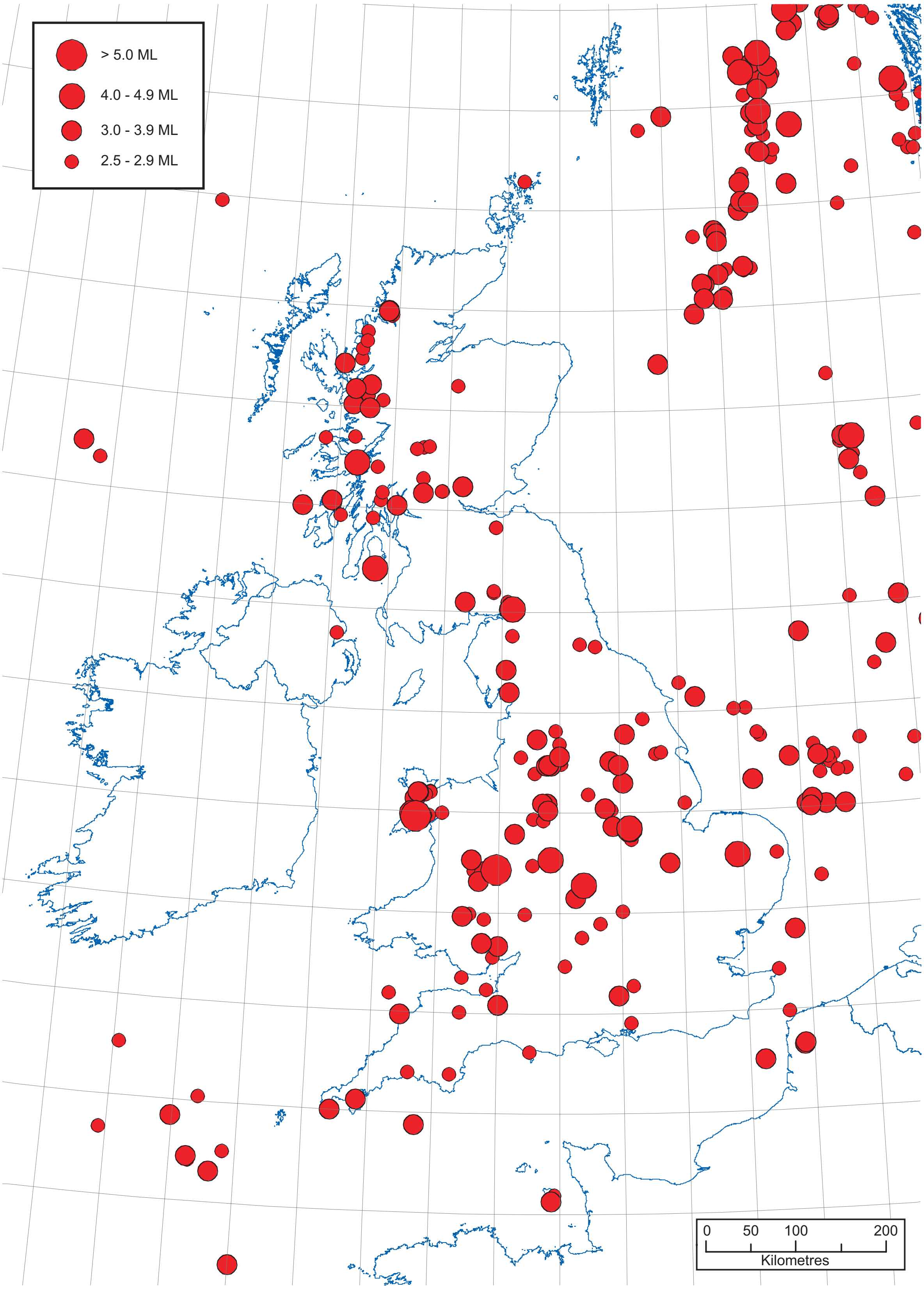
Introduction

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 otherwise 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, some 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 Richter magnitude of 6.1. Fortunately, it was 60 miles offshore but 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 (even for Britain) 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 2004.

Introduction

Monitoring Network

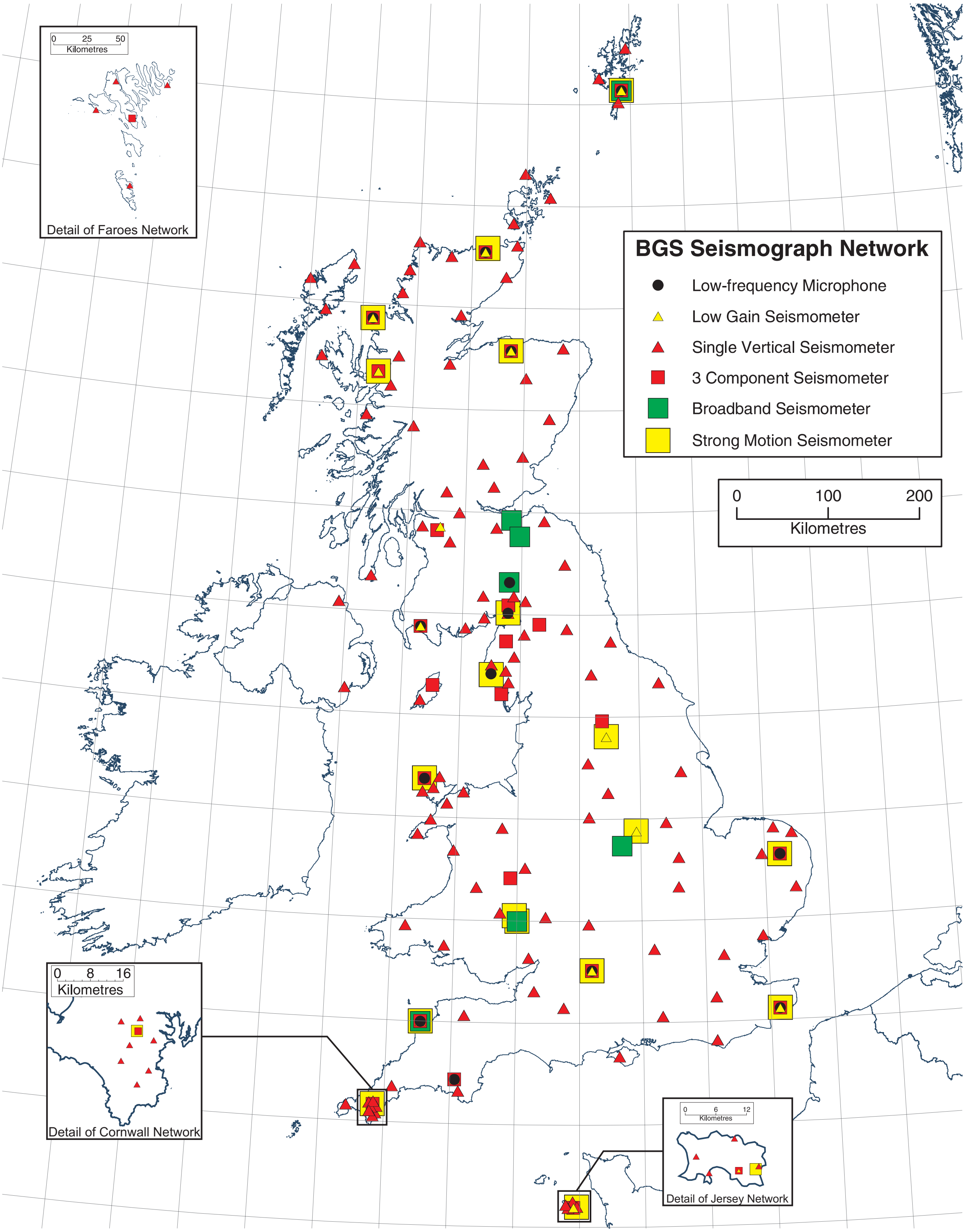
The project started in April 1989, building on local networks of seismograph stations, which had been installed previously for many purposes. Over time, the monitoring network has grown to 146 stations, with an average spacing of 70 km, giving UK-wide coverage and a detection threshold of 2.5 ML for 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 monitoring 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 record 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 5-10 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.



BGS seismograph stations, March 2005.

Achievements

Network Development

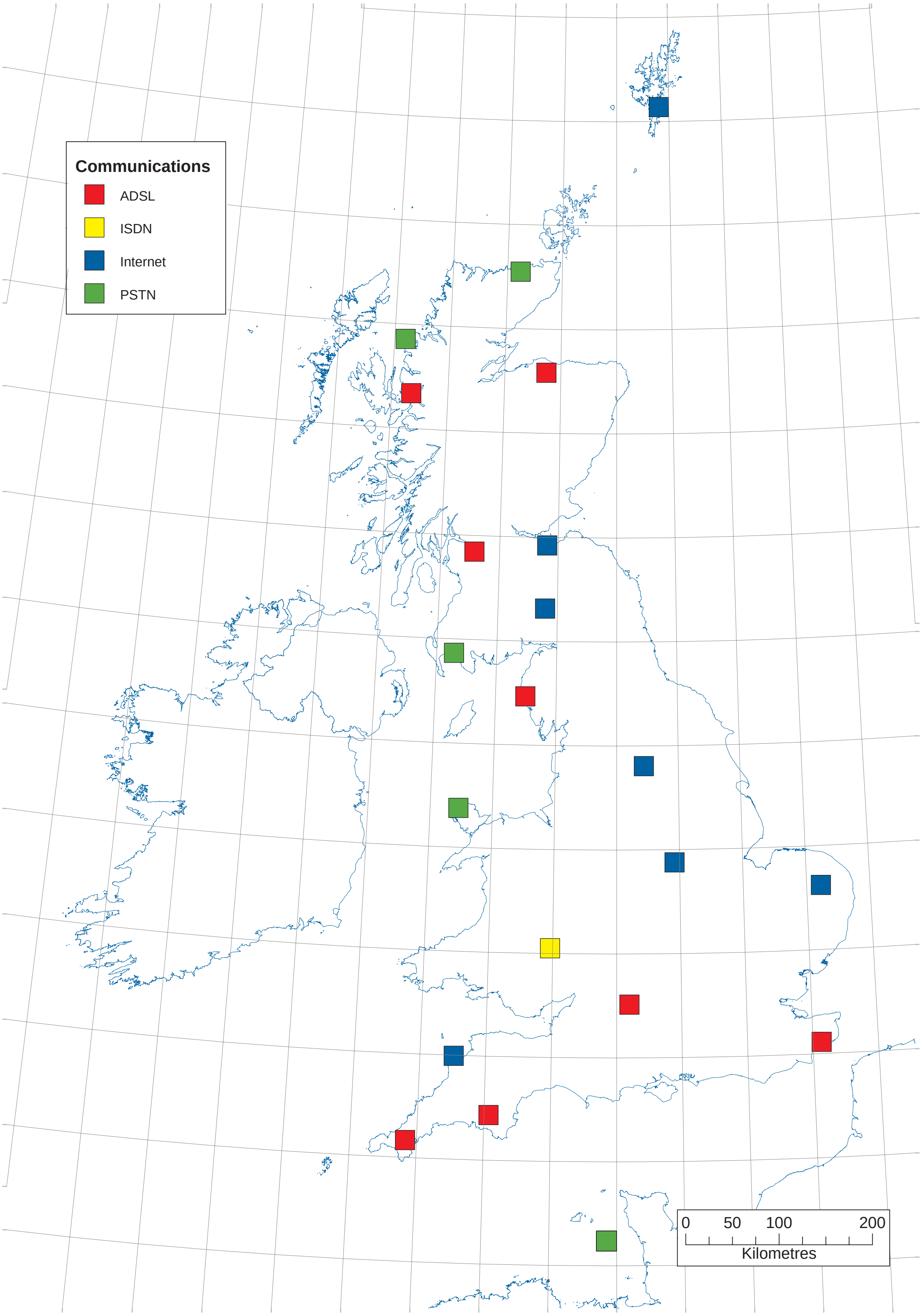
Broadband sensors with 24-bit acquisition are being deployed to improve the quality of the data in terms of signal dynamic range and frequency bandwidth. This will improve the scientific value of the data and add value to services provided to customers.

In the last year two new broadband stations have been installed at Broadlaw (Lothian) and Eskdalemuir (Dumfries and Galloway). Continuous data from both stations are transmitted in real-time to Edinburgh, where they are archived. Data from the MOD station at Wolverton in Berkshire have also been incorporated into the data stream. 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.

Two strong motion accelerometers have been deployed at Sellafield, Cumbria as part of a site-specific monitoring project for British Nuclear Fuels plc. Data from these stations are also available in near real-time at Edinburgh. These instruments also use high dynamic range acquisition, giving an effective recording range of between 1 μg-0.5 g.

The three-component short period sensor near Kyle of Lochalsh has been upgraded to use high-dynamic range, 24-bit, acquisition. The strong motion accelerometer at this site has also been upgraded to use similar technology.

Major upgrades were made to the communications infrastructure at our network base stations across the country. Telephone links to Cornwall, Cumbria, Devon, Kyle, Moray, Paisley, Southeast England and Swindon have been upgraded to use high-speed ADSL connections. In addition, base stations at East Anglia, Eskdalemuir, Keyworth, Shetland, Hartland and Leeds all have high speed Internet connections, either over dedicated links or through agreements with host universities. We expect to be able to upgrade the telephone links at Jersey and North Wales to ADSL this year. This will mean that over 80% of our continuous seismic data can be transferred in near real-time to Edinburgh, which gives huge benefits in terms of network automation and provision of a rapid response. BGS has also greatly increased storage and archival capability at Edinburgh. We now have 70 Terra-bytes of online storage and 80 Terra-bytes of tape archive storage available on site to store and archive large volumes of continuous seismic data.



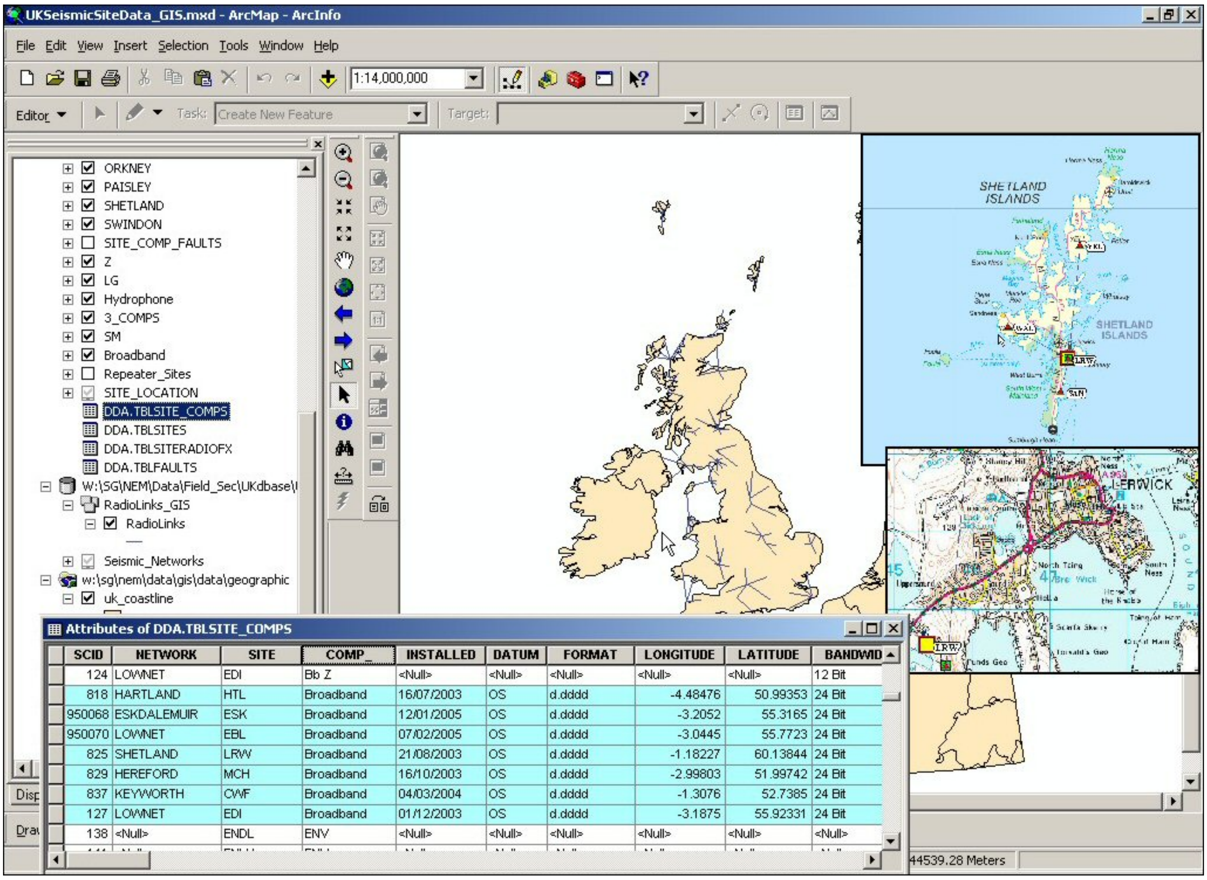
Communications links to UK seismograph network base stations.

We have developed an Oracle relational database to contain all the information about the seismograph network. The database has been designed to allow field engineers and seismologists to manage and access information easily. This will improve the everyday running of the seismic network and help to better understand the layout of the sites and the logistics involved in maintaining them.

There are two front-ends to the database for editing and viewing. A Microsoft Access front-end allows the recording of changes made to new and present sites. This allows access to details such as site locations, stock control, rental information, data acquisition system configurations, field trip recordings and fault reporting. Automated forms allow this data to be managed and, in doing so, a history of changes at the various sites is made. This data can be displayed in various reports, which aid in the planning and management of the seismic networks.

Arc GIS is used to give a visual representation of the seismic stations in the UK. The user can view the individual sites, components, faults and radio links on a layered map. This data is displayed using various keys and labels allowing for quick evaluation of information.

We have continued to develop our new data acquisition software, SDAS, to expand functionality. Eventually this will replace the previously used SEISLOG software. SDAS has the important benefit of increased flexibility and ease of maintenance compared to the SEISLOG system and is used at a number of networks.



Achievements

Information Dissemination

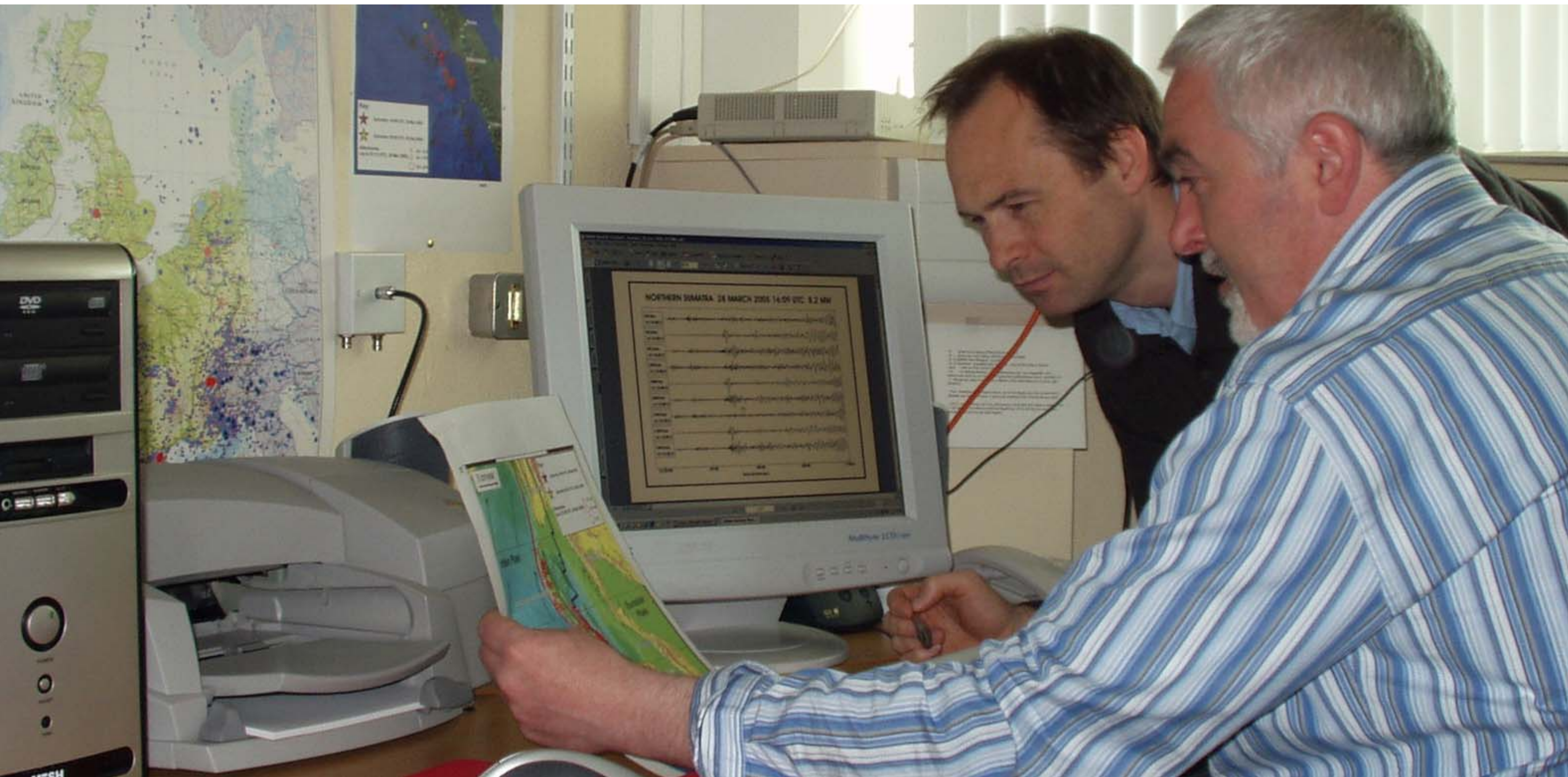
It is a requirement of the Information Service that objective data and information be distributed rapidly and effectively after an event. Customer Group members have received seismic alerts by e-mail whenever an event was felt or heard by more than two individuals.

Alerts were issued for 16 UK events within the reporting period, five of which were of sonic origin, and for 16 global earthquakes. Typically, the information is provided 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 historical setting. In addition, three enquiries were received from Nuclear Power Stations after alarms triggered, and a response was given within 15 minutes in all cases.

Following the catastrophic Sumatra earthquake and tsunami of 26 December 2004, we rapidly provided information to emergency rescue services, government departments, including the Foreign and Commonwealth Office and the Department for International Development, and provided advice to government scientific advisors.

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.

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 2004, it was issued within four months.



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 exchanged data with European and world agencies.

A project with the University of Liverpool and Imperial College London started in September 2004 and is using micro-earthquake data collected by the BGS to derive a new attenuation model for Britain. A CASE student is using the method of Rietbrock (2001), an approach to inversion for the Q structure that combines the use of "spectral shape information" with the use of absolute amplitudes. This approach strongly decouples the determination of geometrical spreading, path and site attenuation and the stress parameter (Brune stress drop). As well as improving understanding of seismic hazard the resulting attenuation relationship will be used to determine accurate source parameters for UK earthquakes, including seismic moment and stress drop, to improve understanding of UK seismicity.

Once reliable estimates of the source (stress parameter) and path and site attenuation parameters have been obtained, these will be used to generate synthetic ground motions for a wide range of magnitudes and distances using the stochastic method (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.

A project with the University of Leicester also started in September 2004 and is using earthquake data from North Wales recorded on the BGS network to improve our understanding of the crustal structure of the North Wales region. P- and S-wave travel times will be used to jointly invert for earthquake hypocentres and crustal velocities (Kissling *et al*., 1994). The resulting seismic velocity models will be used as a starting point for local earthquake tomography (Thurber, 1993).

The Sumatra earthquake of 26 December 2004 and the devastating tsunami that resulted led many governments and agencies to examine the possibility of similar events occurring in other parts of the world. BGS has led a collaborative study with the Proudman Oceanographic Laboratory, the Met Office and HR Wallingford to consider the likelihood and potential impact of such an event affecting the UK. The final report has recently been submitted to DEFRA.

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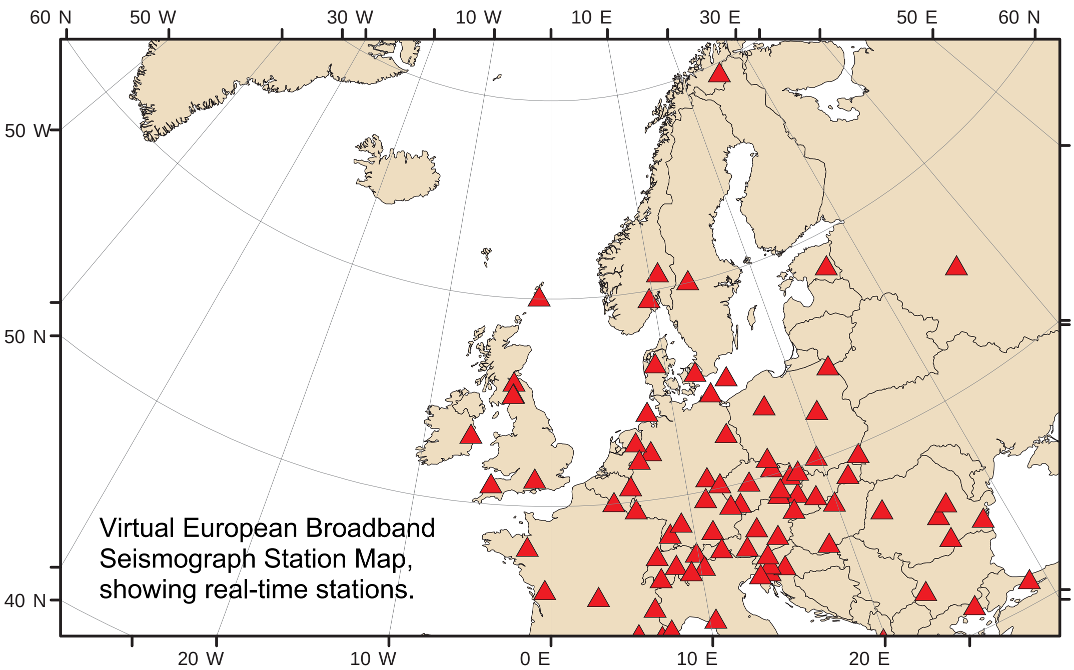
Imperial College London and BGS have worked together on a review of UK procedures in the nuclear industry. BGS and Imperial College have also worked together on an ongoing seismic hazard project in the United Arab Emirates.

The PSIGN project, funded by the European Space Agency and involving Nigel Press Associates, BGS, Imperial College London and TeleRilevamento Europa (Milan), was completed in 2004. The project aim was to investigate the application of new forms of space-based radar remote sensing for studies of tectonics and seismic hazard.

Collaboration with the University of Bergen, Norway, has focused on the magnitude 6.0 Mw earthquake and associated aftershocks near the volcanic island of Jan Mayen in the North Atlantic. The activity was related to the Jan Mayen Fracture Zone that links the mid-Atlantic Ridge systems to the north and south. The aftershocks were studied in detail applying a cross-correlation technique and jointly located to resolve the relation to the mainshock. The results were interpreted in the light of recently acquired detailed bathymetric data in the vicinity of Jan Mayen. This work is significant as aftershock recordings from the mid-Atlantic ridge are rare.

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.



Virtual European Broadband Seismograph Station Map, showing real-time stations.

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.

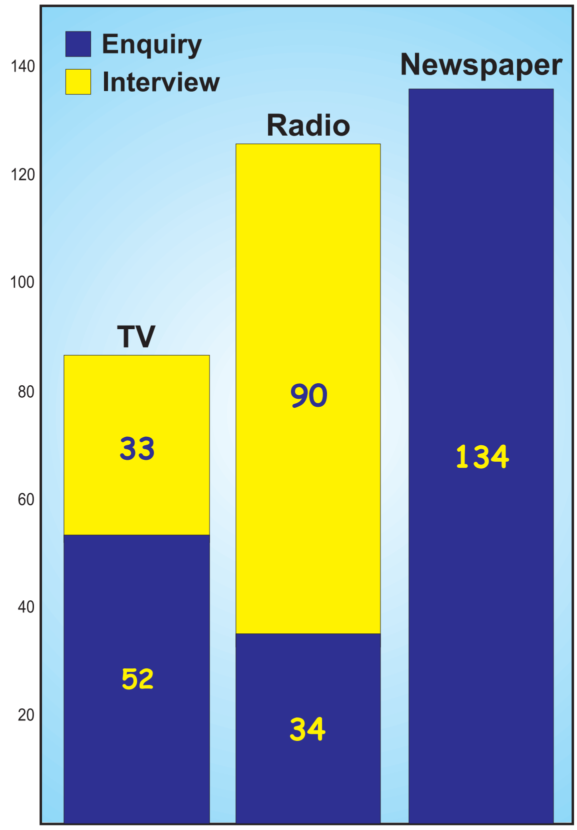
A number of lectures and presentations were given to schools, university students and other interested parties. The BGS Open Day in September attracted 803 visitors with many of them visiting the interactive earthquake display. A further 200 school pupils visited during the following Schools Week.

Almost all of the 5000 earthquake information booklets produced in August 2003 have been distributed. This booklet provides information on earthquakes and their causes in a simple and easily digestible form and has been used in school educational packs, at workshops for schools, at various science festival events throughout the country, as well as for general enquiries and requests for information about earthquakes. A PDF version of the document is available for download from the Seismology web site. We will start working on a new version of the booklet in the coming year.

The Seismology web site continues to be widely accessed, with over 323,000 visitors (2.0 million hits) logged. Significant peaks were observed in December and January and special pages were published containing detailed information on the Sumatra earthquake. 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 2004-2005, 802 enquiries were answered. Some 343 of these were from the media, including 209 for TV and radio broadcasts following significant earthquakes. The broadcasting enquiries led to 33 TV and 90 radio interviews.

Team members contributed articles following the Sumatra earthquakes in the Daily Mirror, Scotland on Sunday and the Scotsman newspapers. Roger Musson appeared on the BBC Timewatch documentary on the flooding around the Bristol Channel in 1607. Brian Baptie appeared in a documentary on the Sumatra earthquake and tsunami produced for Christian Aid.



Seismic Activity

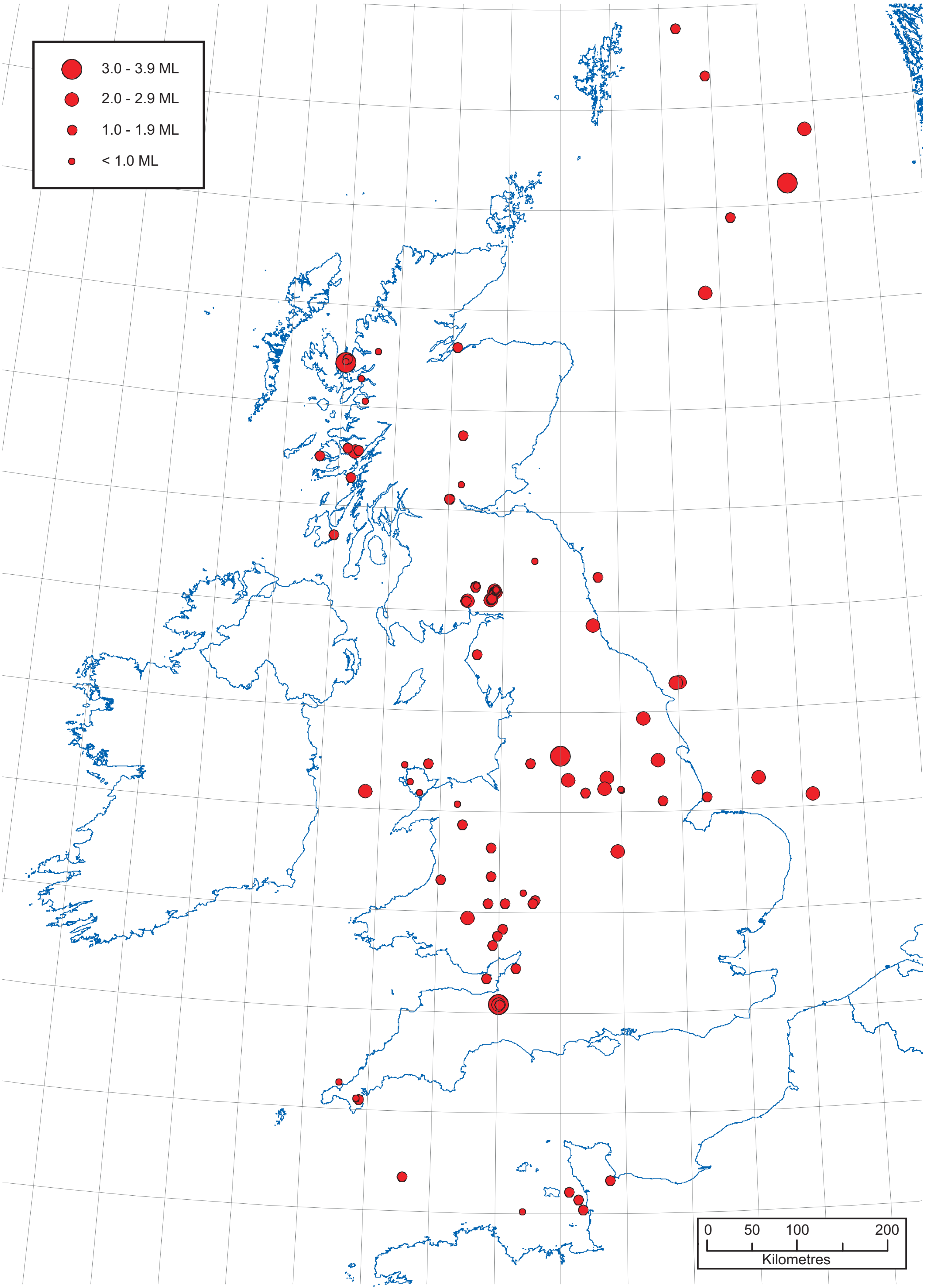
The details of all earthquakes, felt explosions and sonic booms detected by the network have been published in monthly bulletins and compiled in the BGS Annual Bulletin for 2004, published and distributed in April 2005 (Simpson, 2005).

There were 131 earthquakes located by the monitoring network during the year, with thirty of them having magnitudes of 2.0 ML or greater. Ten events with a magnitude of 2.0 ML or greater were reported, together with a further ten smaller ones, bringing the total to 20 felt earthquakes in 2004. The largest onshore earthquake had a magnitude of 3.3 ML and occurred near Raasay on 16 September 2004. The largest offshore earthquake occurred in the Northern North Sea on 13 May 2004, with a magnitude of 3.5 ML. It was located approximately 270 km east of Lerwick, Shetland Islands.

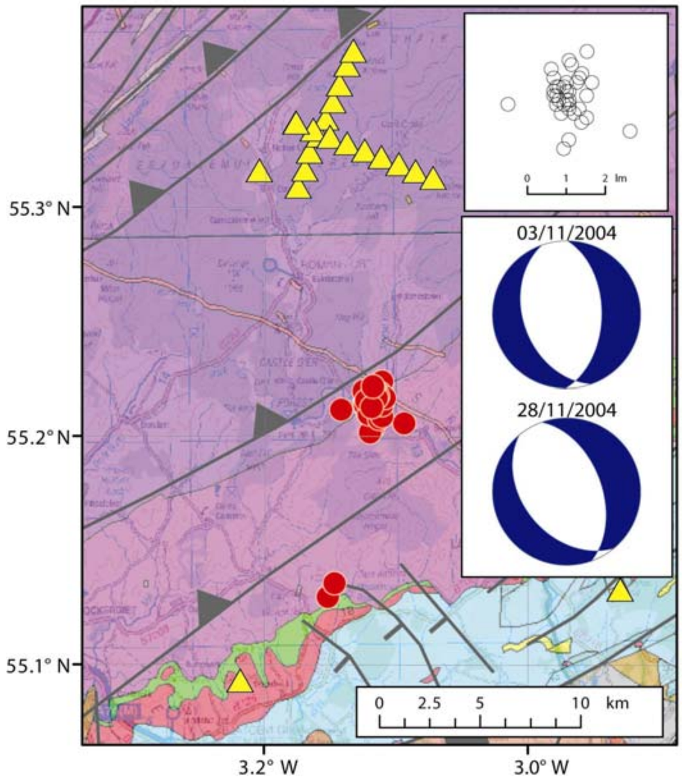
The spatial distribution of seismicity in 2004 generally reflects that observed in the instrumental catalogue as a whole, with the majority of earthquakes occurring in and around Wales, Cornwall, the Midlands, Cumbria and the Scottish Borders and in western Scotland. There was also activity in the northern and southern North Sea. No events were recorded in southeast England, Ireland, or the Outer Hebrides. 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 2004 to March 2005, a total of 397 teleseismic earthquakes were detected and analysed.

In the following sections, we provide more detailed reports of an interesting earthquake sequence near Eskdalemuir, Dumfries and Galloway, and a magnitude 3.3 earthquake near Conwy, (2005), North Wales (an area where there has been considerable seismic activity over the past thirty years). We also report on the catastrophic Sumatra earthquakes of 26 December 2004 and 28 March 2005.



Epicentres of all UK earthquakes located in 2004.



Seismic Activity

Eskdalemuir

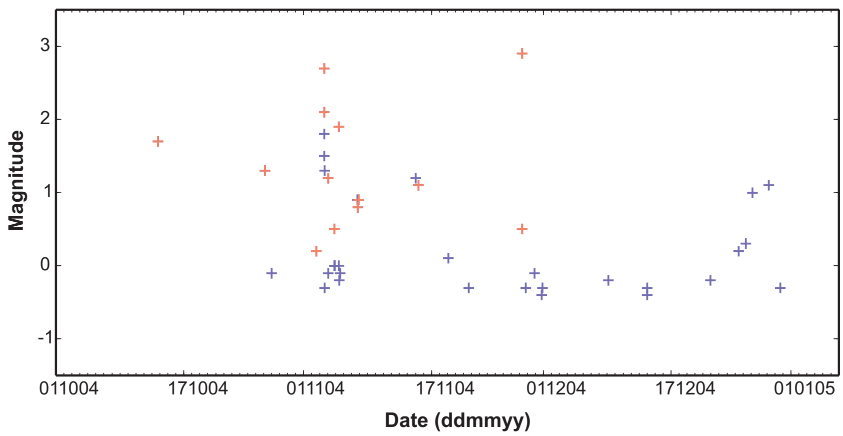
Highly correlated waveform signals were observed from a sequence of earthquakes near Eskdalemuir. Cross-correlation techniques were applied to these events to better resolve relative locations.

A total of 41 earthquakes were recorded about 15 km southeast of Eskdalemuir between 13 October and 30 December 2004. Nine of the events were felt at nearby villages. The two largest events occurred on 3 November at 13:34 (UTC) and 28 November at 08:11 with magnitudes 2.7 and 2.9 ML. The proximity of the earthquakes to seismic stations allowed us to detect events with magnitudes as small as -0.4 ML.

Initial analysis suggested that the spatial extent of the earthquake source region was less than a few kilometres. We applied a cross-correlation technique, which identified three groups of similar events consisting of thirteen, three and two events. Timing of phases as well as amplitude ratios was nearly identical within the groups. The main group contained the two largest earthquakes, suggesting that these two events had a similar hypocentre location and source mechanism. The focal mechanisms for the two largest events show normal faulting with the two nodal planes striking in a N to NNW direction and dipping either west or east.

Accurate and consistent phase arrivals were determined for events of the largest group using the cross-correlation technique. The resulting phase arrivals were input, together with the manually picked arrivals for the other events, to a joint location procedure. The majority of the earthquakes originate from an area about 2.5 km in north-south and 1 km in east-west direction.

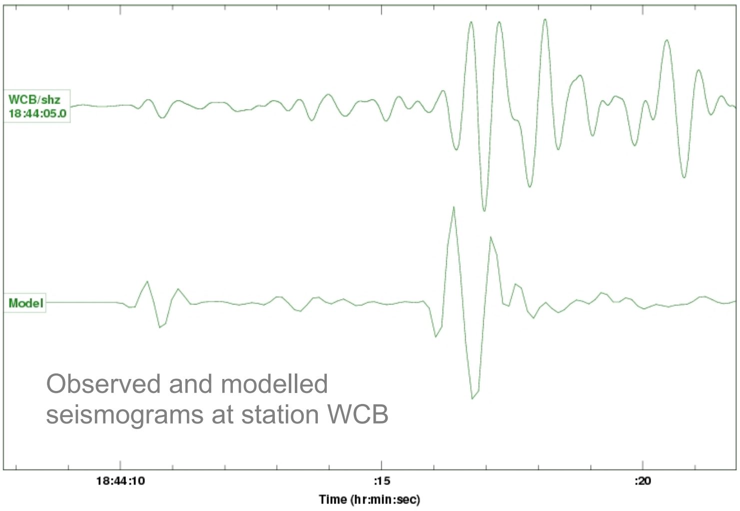
The distribution of epicentres is clustered and shows no clear linear trend that may indicate a fault plane. The larger faults in the region are oriented southwest northeast, perpendicular to the nodal planes of the two largest events in the sequence. The event distribution and tectonic information, therefore, cannot be used to identify one of the nodal planes as causative fault.



Magnitude distribution as a function of time. Events belonging to the group of the largest group of thirteen similar events are plotted red. All other events are blue.

Seismic Activity

Conwy

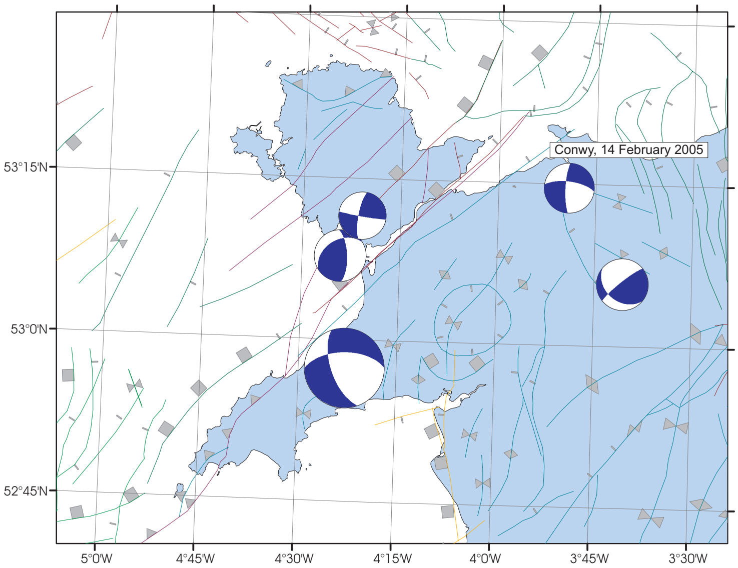


Observed and modelled seismograms at station WCB

Significant media and public interest was created on 14 February 2005, when an earthquake was felt in North Wales, at 18:44 (UTC) with a maximum intensity of 4 (EMS). The epicentre was determined to be about 5 km south of Conwy with a magnitude of 3.3 ML.

The earthquake location was well determined with horizontal errors of 1.8 and 2.5 km in the north-south and east-west directions respectively. The *RMS* error in the travel-time residuals was 0.27s and the azimuthal gap in the stations used for locating the earthquake is 39°. The depth was calculated at 10.2 km with an error of ±2.3 km.

We determined a source mechanism for the earthquake from first motion polarities. The grid search method of Snoke *et al*. (1984) was used to determine the best-fitting fault plane solutions, with a grid spacing of 2°. Sixty-six possible solutions were found to fit the observed polarity data, which all showed very similar fault motion. The solutions show either left lateral strike-slip motion on a north-south fault dipping slightly to the west, or right lateral strike-slip motion on an east-west fault dipping slightly to the north. The *P*-axis orientations agree well with the regional tectonic model, which predicts northwest compression.



We then generated synthetic seismograms using the method of Herrmann (1996) to determine the reliability of the source parameters. The models accurately capture many of the key characteristics of the observed data in terms of both waveform shape and relative amplitude of the different arrivals. This suggests we can be quite confident in our source parameters.

We can also compare our source mechanism with the observed surface faulting in the region and focal mechanisms for other earthquakes in North Wales. In general, many of the regional tectonic features strike southwest northeast. However, the Colwyn Bay earthquake lies at the northern end of a near north-south striking fault that runs along the line of the Vale of Conwy and provides a good match to the possible fault plane solutions.

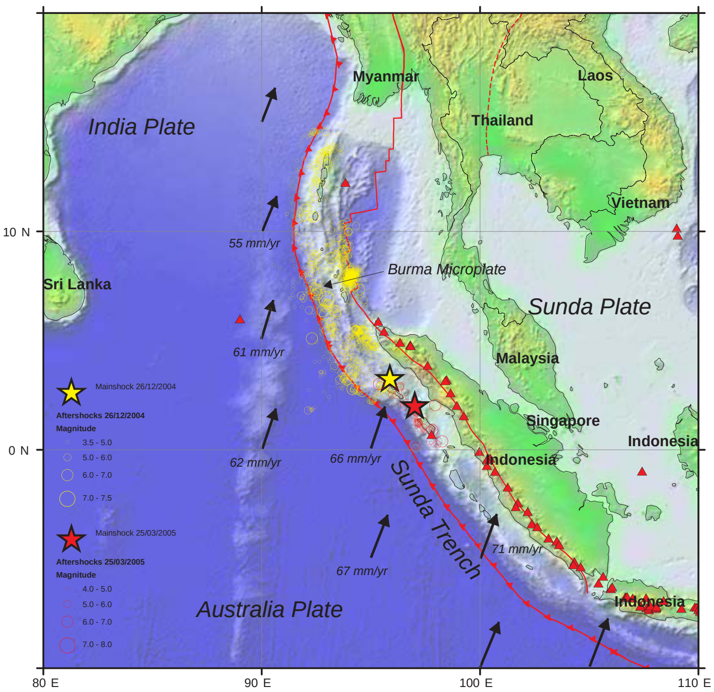
Seismic Activity

Global Earthquakes

The devastating Sumatra earthquake and tsunami caused massive loss of life all around the Indian Ocean. Recent estimates of the death toll suggest that over 280,000 people lost their lives. Affected areas included Sumatra, Thailand, Sri Lanka, India and the east coast of Africa. The tsunami was a truly global event and was recorded in the Pacific and Atlantic Oceans.

An aerial view of the ruins of a housing complex in the Indonesian city of Banda Aceh three days after the disaster. REUTERS/Beawiharta

At 00:58 GMT on Sunday 26 December 2004, a 1200km long segment of the plate boundary between the Indian and Burma plates ruptured causing a magnitude 9.3 earthquake (Stein and Okal, 2005). The earthquake occurred along a thrust zone as the Indian plate is subducted beneath the over-riding Burma plate along the line of the Sunda Trench. The Indian plate is moving approximately northeast at a rate of around 6 cm per year at an oblique angle to the Sunda Trench. Stress had accumulated along this thrust zone for hundreds of years until it finally reached a critical point and failed.



The distribution of aftershocks suggests that the rupture that caused the earthquake extended from the north west coast of Sumatra to the Andaman Islands, over 1200 km away. The width of the fault rupture is estimated at about 100 km and the maximum displacement on the fault plane was about 20 metres, most of this concentrated in the southern 400 km of the rupture. The rupture took several minutes to propagate from the epicentre to the northern end of the fault.

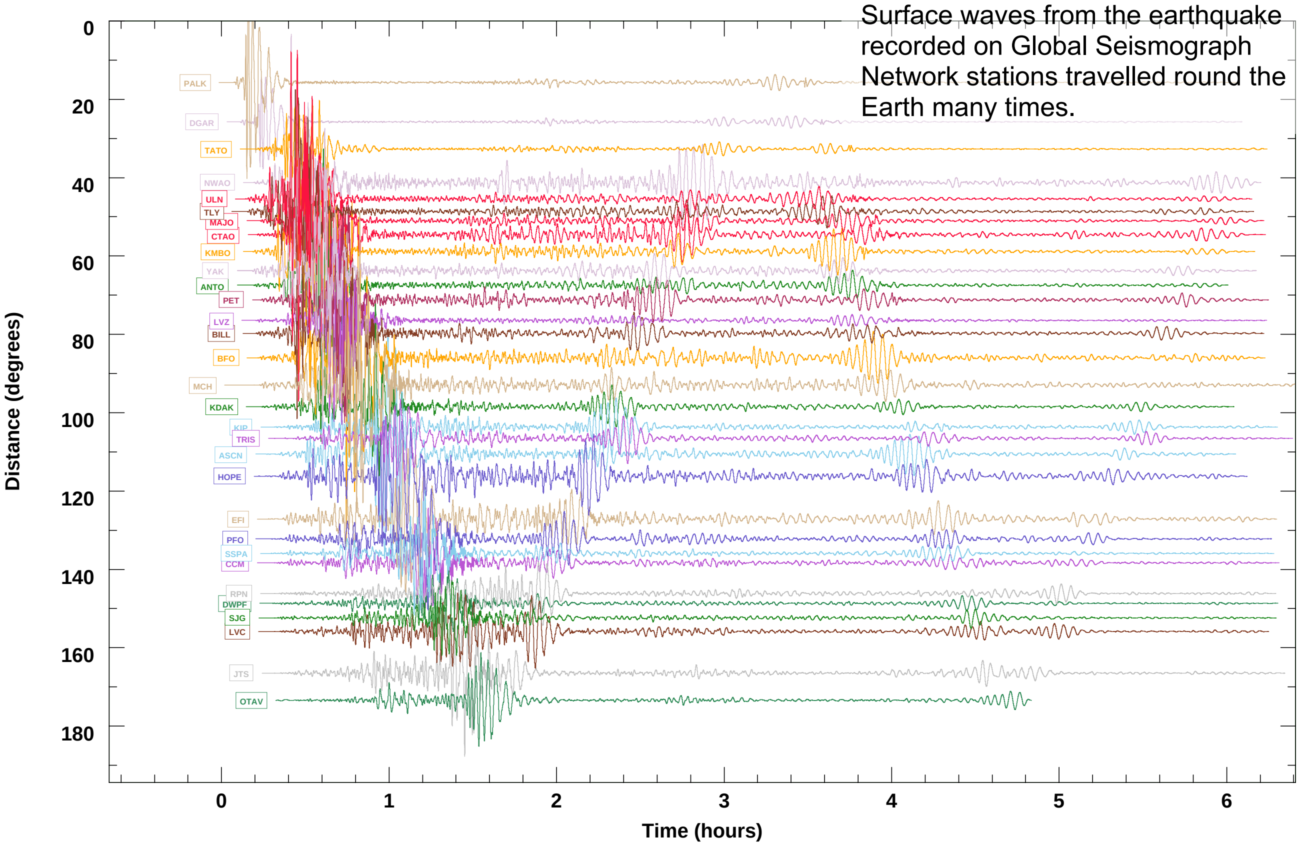
The devastating tsunami was a direct consequence of the earthquake, which caused movement of the seafloor all along the length of rupture, generating the tsunami wave. The vertical uplift of the seafloor could have been as much as several metres, displacing an enormous volume of water. In the deep water of the Indian Ocean the tsunami wave would have travelled at around 700km/hour, taking around two hours to reach the coast of India and Sri Lanka.

Onlookers look at damaged fishing trawlers stuck on a bridge in Nagapattinam port, 350 km south of the Indian city of Madras on 29 December, 2004. REUTERS/Punit Paranjpe

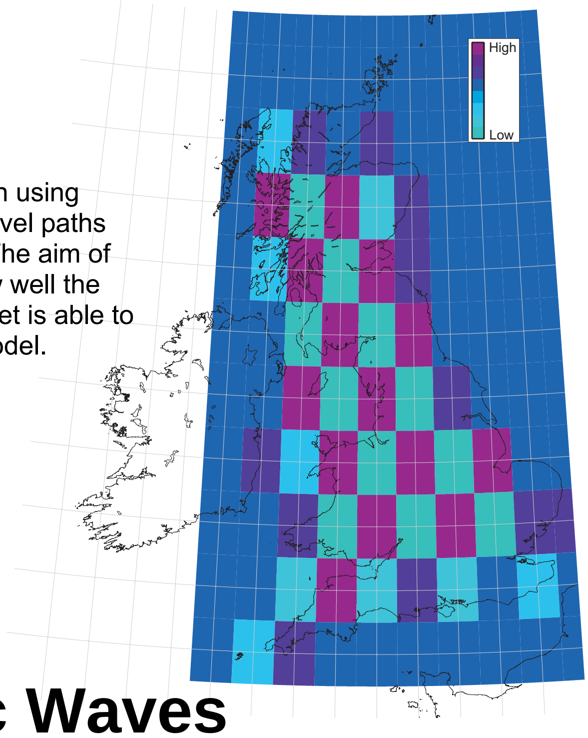
On 28 March at 1609 GMT another massive earthquake struck off the west coast of Sumatra, causing widespread panic in the region and fears of a further tsunami. The epicentre of the magnitude 8.7 earthquake was about 150 km southeast of the magnitude 9.3 event that occurred on 26 December 2004. However, this earthquake did not trigger the widely expected destructive tsunami, although tide gauges in the Indian Ocean did show changes to the expected sea level, with wave heights of 10-20 cm measured on tide gauges in Sri Lanka, the Cocos Islands and the Maldives.

It is likely that this earthquake was triggered by stress changes caused by the earthquake on 26 December 2004. When large earthquakes occur on one part of a fault zone, stress can be transferred to another part of the fault zone that didn't rupture during the initial event, or even to other nearby faults, and this can increase the probability of another large earthquake in the near future in these zones. McCloskey *et al.* (2005) examined the possible stress changes caused by the December 26 earthquake. They concluded that there was an increased likelihood of another large earthquake either in the Sunda trench subduction zone, which lies off the southwest coast of Sumatra, or along the neighbouring Sumatra fault, that runs northwest to southeast through the middle of Sumatra.

The phenomenon of stress transfer has been widely observed, for example the magnitude 7.4 Izmit earthquake that occurred southeast of Istanbul in 1999, led to transfer of stress along the North Anatolian Fault zone, triggering the magnitude 7.1 Duzce earthquake a few months later.



Surface waves from the earthquake recorded on Global Seismograph Network stations travelled round the Earth many times.



Result of a checkerboard inversion using synthetic data calculated using travel paths defined by the dataset (at 8 Hz). The aim of this type of testing is to check how well the configuration of paths in the dataset is able to resolve a simple checkerboard model.

Scientific Objectives

Attenuation of Seismic Waves

Understanding the strength of seismic wave attenuation (the amplitude decay with distance) is important for seismic hazard assessment. In 2004-2005, a revised estimate of average Lg-wave attenuation has been developed using data from the highest magnitude UK earthquakes, and for the first time, attenuation tomography has been investigated (Ottemöller *et al.*, 2002). The results indicate that crustal attenuation is highly variable in a lateral sense, and appears to be controlled by the tectonic and structural fabric of the British Isles.

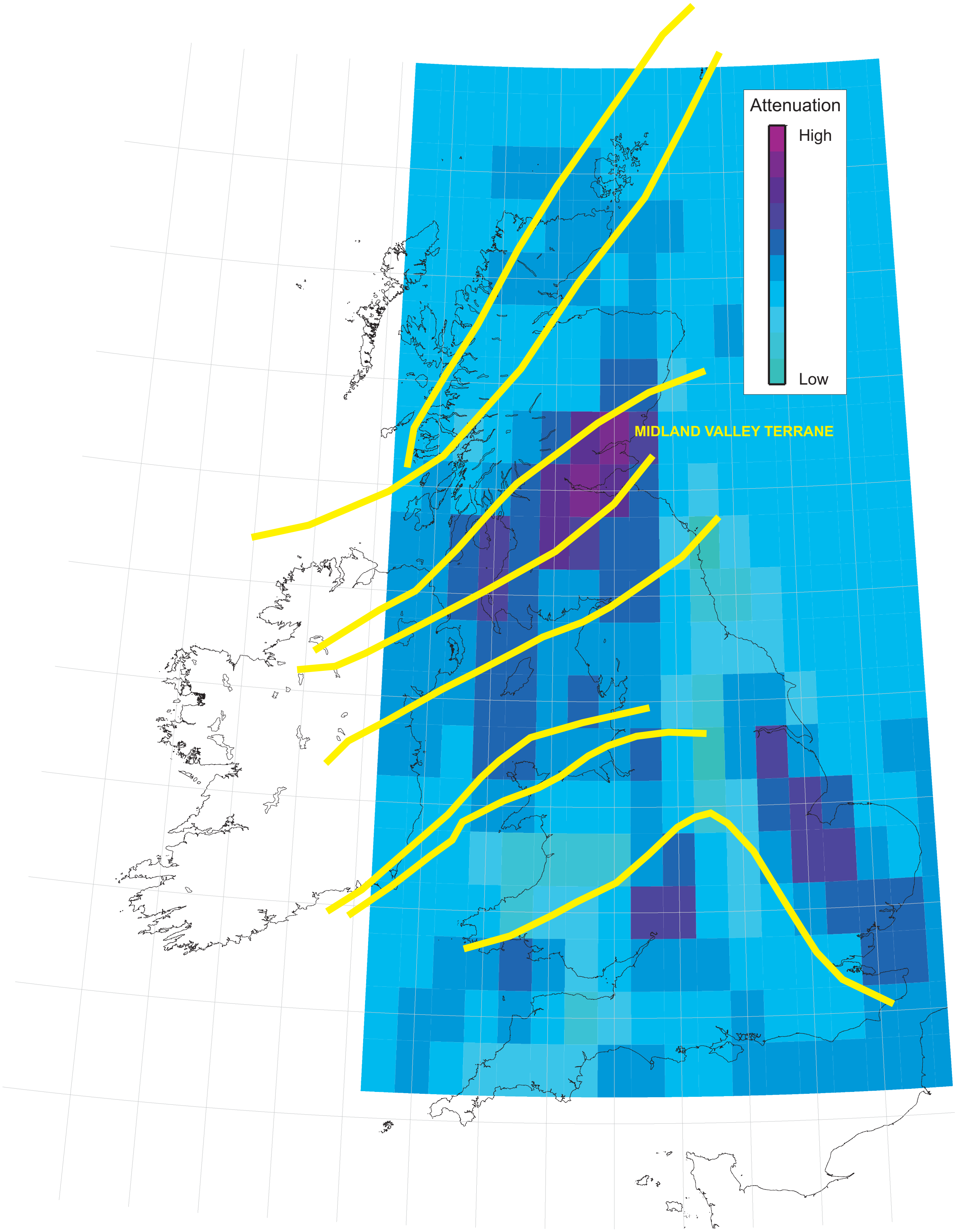
A study of Lg-wave attenuation in the UK was made in 2003, which resulted in the first UK-specific relation for Q(f). This was the first time a relationship for the attenuation of seismic waves in the UK had been determined directly from observations. Lg waves are S-waves that are multiply reflected and trapped in the crust, and are usually observed on seismograms out to distances of several thousand kilometres.

Since 2003, more data from larger UK earthquakes have been included in the investigation. The new analysis shows that average Lg-wave attenuation in the UK can be approximated using the relation

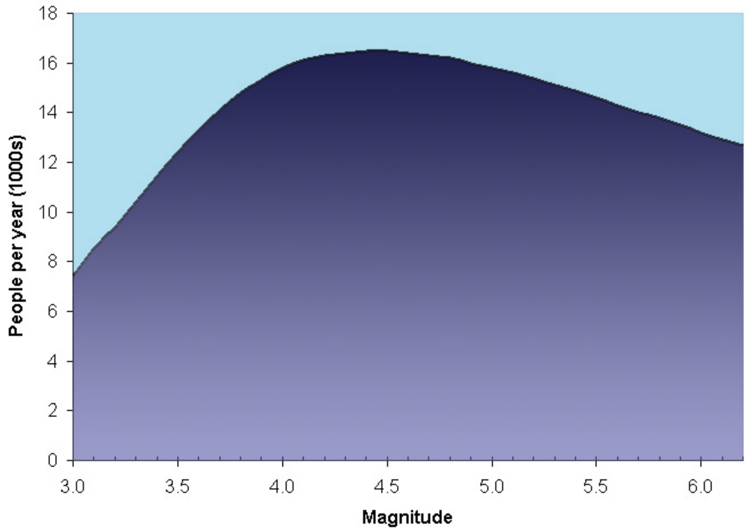
$$Q(f) = 236\, f^{0.63}$$

where *Q*(*f*) is the quality factor for *Lg* (a measure of attenuation). This result indicates that average attenuation in the UK is apparently comparable to that of tectonically active regions such as California, which is a somewhat surprising result.

The tomography results indicate widespread lateral variations in attenuation in the UK. The most striking feature is a region of very high attenuation that coincides with the Midland Valley Graben in southern Scotland. This is likely due to the large thickness of strongly attenuative sediments within the graben. High attenuation in this relatively large region is probably also responsible for the high average regional estimate that is obtained for the UK.



Results of the tomographic inversion for attenuation at 8 Hz. The yellow lines indicate the boundaries between the major tectonic provinces in the UK. Dark blue indicates higher attenuation, as seen across the Midland Valley of Scotland.



Estimate of the average number of people per year in the UK expected to feel an earthquake of a given size.

Scientific Objectives

Design Earthquakes in the UK

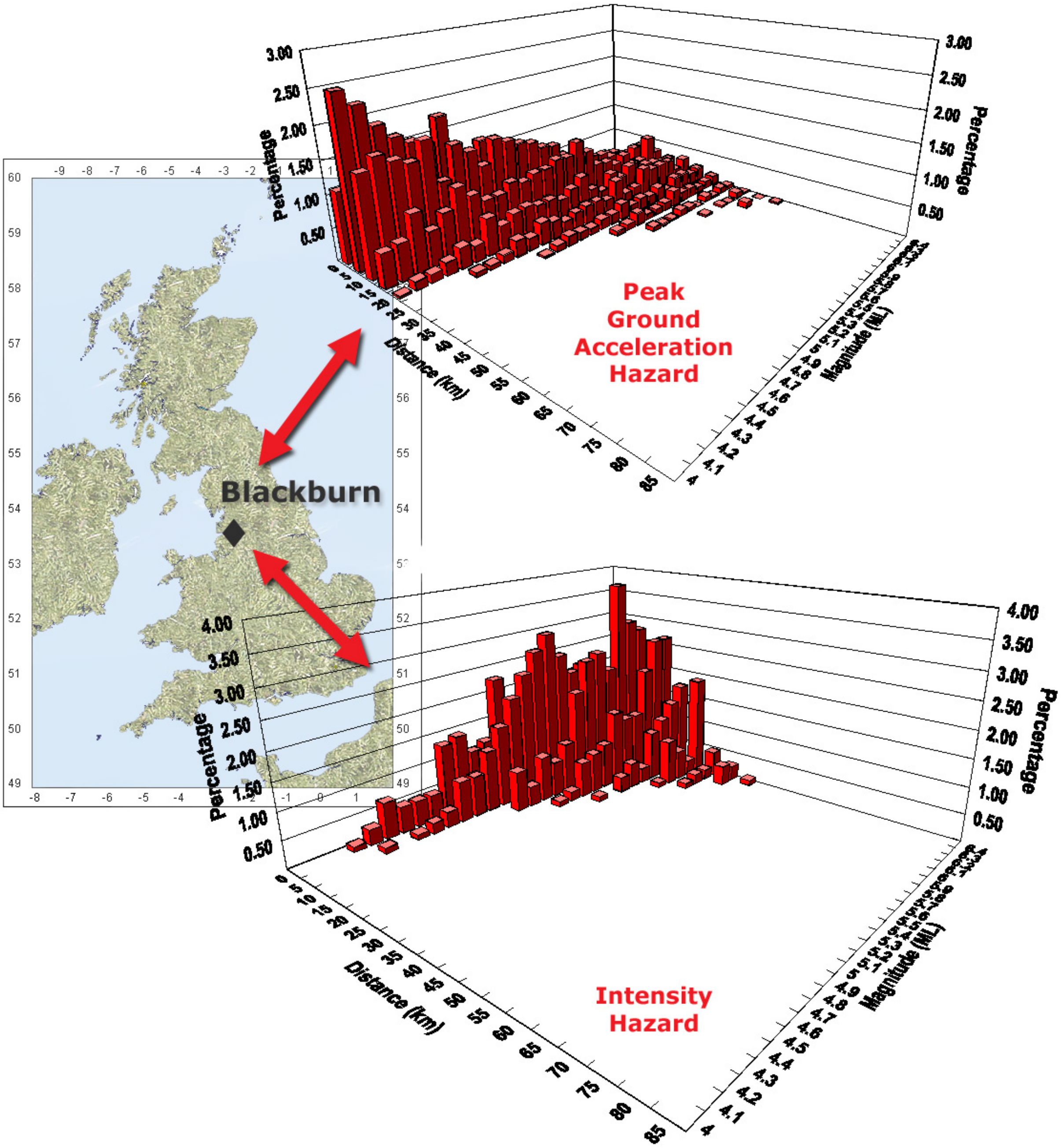
Seismic hazard studies have traditionally focussed on producing a design ground motion (usually peak ground acceleration – PGA) to be used as a basis for engineering design. However, in real life, ground motions are produced by real earthquakes, therefore it helps to know what sort of earthquake one is supposed to be guarding against.

Early hazard work in BGS back in the 1970s looked at the question, “What is the most perceptible earthquake in the UK?” Small earthquakes are common but are felt by few people over a small area. Larger earthquakes are felt by many over a wide area, but are rare in occurrence. Somewhere there has to be a point in the trade-off between size and frequency where one hits a peak of maximum perceptibility.

The same thing happens in engineering seismology. Design ground motions do not exist in isolation, and the engineer asked to design against an acceleration of 0.2 g would like to know if this is from a small earthquake close in, or a larger one further away. There was no way to answer this question routinely until disaggregation techniques were invented in the mid to late 90s. It then became possible to plot the distribution of earthquakes capable of causing a given ground motion, and find the most likely event in terms of magnitude and distance.

The results of such studies in the UK are rather disconcerting; for any hazard value given in terms of PGA (as is most common), one finds that the most likely earthquake to produce the design acceleration is not much over 4 ML. However, earthquakes this size usually produce very little damage. Repeating the exercise using macroseismic intensity, gives a different picture. For the same probability level, the most likely earthquake to produce the design intensity level is around 5.7 ML; in other words, something similar to earthquakes like 1580 Dover Straits, 1938 Mons (Belgium) and 1992 Roermond (Netherlands), which were some of the most damaging earthquakes in NW Europe.

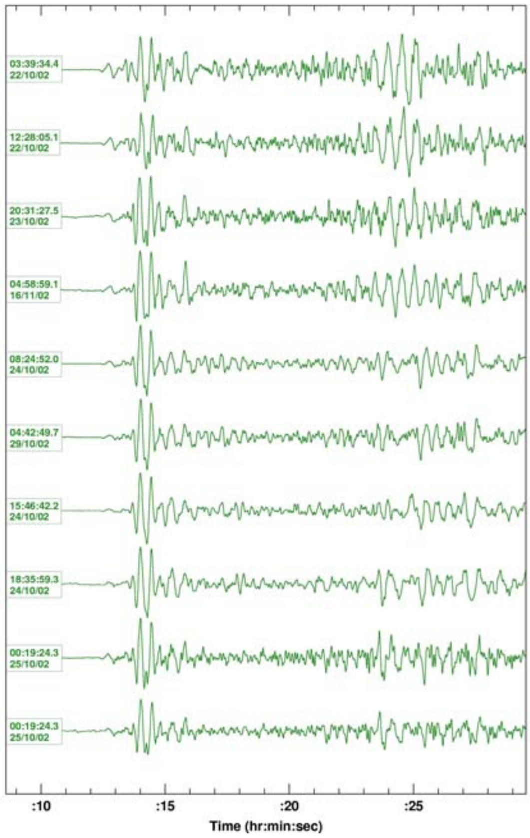
Common sense suggests that these larger events are what UK engineers should be most concerned about. Small earthquakes can produce high PGA values through freak scattering, but high PGA values are not likely to be significantly damaging when they come from high frequency shaking from small sources. In contrast, intensity, though not a physical parameter (and therefore hard to use in engineering design), is closely related to damage. Therefore disaggregation of intensity hazard values gives a better idea of the earthquake that is actually most likely to pose a significant threat to any site.



For an example site at Blackburn, frequency distributions are shown for different magnitude-distance combinations that would produce the PGA and intensity value that have an annual probability of occurring of 1 in 10,000. The two distributions are very unlike. Irregularities in the shape are due to the fact that the distributions were computed using simulations.

Scientific Objectives

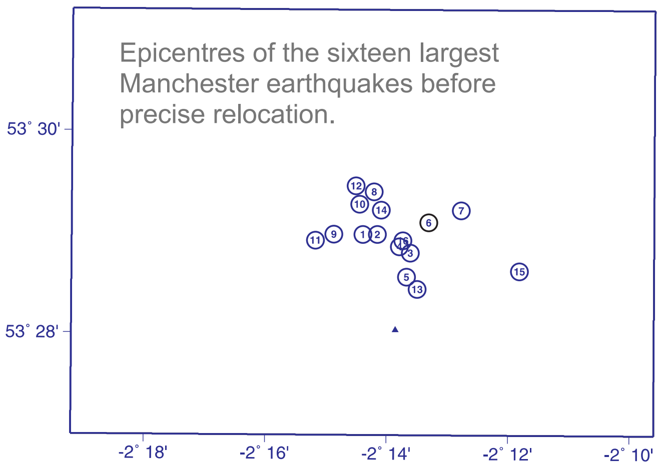
Distribution of UK Seismicity



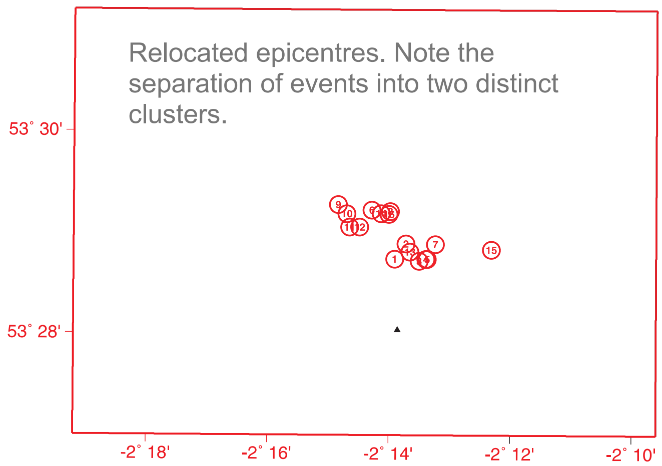
The spatial distribution of earthquakes in the UK is generally diffuse, though with strong regional variation. Seismicity does not appear to be based on individual major active faults, and there is no clear relationship between tectonic province and the spatial distribution of seismicity. Our aim is to apply new methods to improve relative locations within the earthquake catalogue and try to relate earthquake activity to geological features.

Recent studies such as Schaff and Richards (2004) have shown how improvements can be made in relative earthquake locations that may allow earthquake activity to be more accurately related to geological features and improve our understanding of earthquake activity in the UK.

Analysis of earthquakes from the Manchester swarm of 2002 has shown that over 50% of the recorded events are highly correlated with at least one other earthquake in the sequence. Such events must be very closely located with similar source mechanisms. We use hierarchical cluster analysis to group similar events together based on their cross-correlation coefficients at a given station. Master or reference events within each group are then used to determine consistent phase arrivals for all the events in each group. Then we used the double difference method of Waldhauser and Ellsworth (2000) to determine high-resolution hypocenter locations for the dataset. The results show improved clustering in the final hypocenters.



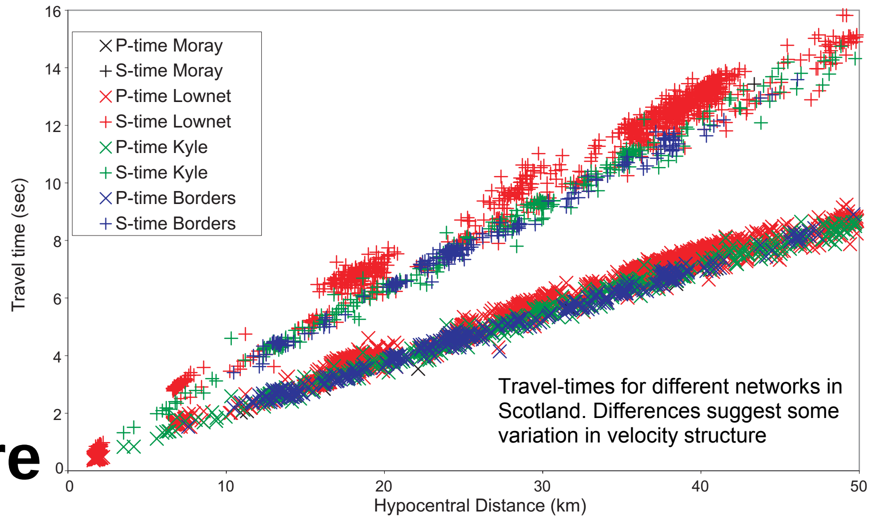
Epicentres of the sixteen largest Manchester earthquakes before precise relocation.



Relocated epicentres. Note the separation of events into two distinct clusters.

Scientific Objectives

Crustal Structure



Travel-times for different networks in Scotland. Differences suggest some variation in velocity structure

Most of the published information on seismic velocity structure in the UK has been obtained from large-scale seismic refraction and wide-angle reflection surveys. Models used by BGS for locating earthquakes are generally derived from such sources and define velocity as a function of depth in a number of discrete areas. However, transitions between different models do not necessarily correspond to structural boundaries and the models themselves do not account for lateral variations in the earth.

P- and S-wave travel times for Scottish earthquakes recorded on the BGS seismograph network have been used to jointly invert for earthquake hypocentres and crustal velocities beneath Scotland using the method of Kissling *et al.* (1994). Velocity information from refraction and reflection lines and other studies were used to help constrain the initial starting model, since the results of the inversion can be strongly dependent on the choice of starting model.

As well as to develop a new regional model that can be used as a starting point for local earthquake tomography (Thurber, 1993), we used two smaller subsets of earthquakes from different areas to examine the regional variation in velocity structure.

Using a number of starting models, we obtain reasonable convergence of velocities between depths of 3-20 km in both the Southern Uplands and Central and Western Scotland. The convergence improves as the number of layers in the model decreases. However, the velocity of the top layer is strongly dependent on starting velocity and cannot be resolved using this method. Near-surface velocities have been determined from *a priori* sources.

The resulting model for Central and Western Scotland does not differ greatly from the existing Lownet velocity model, but has a higher velocity in the near-surface and slightly lower velocity at depth. The Southern Uplands velocity model is similar to that determined from the LISPB refraction profile Bamford *et al*. (1978), but again, near-surface velocities are higher than those used in either the Lownet or Borders velocity models.

In a separate study, we have used analysis of variance (Carpenter *et al.*, 1967) to determine traveltime-distance curves and station corrections for *P*-wave traveltimes in different regions of the UK. This method allows a traveltime-distance relation to be calculated without the need for accurate timing of the event origin time. The results of both studies show reasonable agreement.

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 scientific 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

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

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Davie Galloway	Seismologist
Bennett Simpson	Seismologist
Julian Bukits	Seismologist

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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
Freya Lawrie	Software Engineer

Consultants	
David J Kerridge	Programme Leader
Margaret Milne	Programme Secretary

Appendix 2 Publications

BGS Internal Reports

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

Sargeant, S.L. and Musson, R.M.W., 2004. Subduction zones with potential for PSInSAR investigation for space-based disaster reduction, British Geological Survey Technical Report, CR/04/158N.

Simpson, B.A. (ed), 2005. Bulletin of British earthquakes 2004, BGS Report CR/04/074N.

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

Albini, P., García Acosta, V., Musson, R.M.W. and Stucchi, M. (eds), 2004. Investigating the records of past earthquakes, Proc. 21st Course of the Int. School of Geoph., Erice, Sicily, Jul 2002, Annals of Geophysics, vol 47 nos 2-3, 911 pp.

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Musson, R.M.W., Haynes, M. and Ferretti, A., 2004. Space-based tectonic modelling in subduction areas using PSInSAR, Seis. Res. Letters, vol 75, pp 598-606.

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Sargeant, S.L. and Musson, R.M.W., 2004. Attenuation of PGA from small UK earthquakes, ESC XXIX General Assembly Abstracts, Potsdam, p202.

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Appendix 3 Publication Summaries

Investigating the records of past earthquakes

P. Albini, V. García Acosta, R.M.W. Musson and M. Stucchi (eds)

The International Workshop on "Investigating the records of past earthquakes" was held on 1-7 July 2002, at the "Ettore Majorana Scientific Center", Erice (Sicily), as the 21st Course of the International School of Geophysics, under the auspices of the Istituto Nazionale di Geofisica e Vulcanologia. The contributors and participants were 80 in all, and they came from 30 different countries throughout the world. This was the first occasion for a worldwide coming together of the principal exponents of historical seismology from every continent with the obvious exception of Antarctica.

The Workshop was divided into two main sessions: the first, on "Assessing the state-of-the-art of historical earthquake investigation" allowed contributors to describe in detail results and plans for the future development of this subject in their countries; the second on "Selected case histories, methodological aspects, complementarity with other data and potential contribution of historical earthquake records" went from showing investigation on individual earthquakes to new frontiers of interpretation and use of historical earthquake data in hazard assessment.

As far as possible, the 41 papers in this volume provide an overview of the state of the art in historical seismology across the globe. For some countries representatives were present at the workshop even though no written paper could be included from them in this volume. Some of the papers in this volume concentrate on describing the stages that historical seismology went through in the authors' country; others focus on case studies that reveal something of the particular nature of historical seismological problems in that country. Taken as a whole, they provide a global panorama of research activities into the earthquakes of the past, that will contribute materially towards strengthening human communities to withstand the earthquakes of the future.

The Manchester Earthquake Swarm of October 2002

B. Baptie and L. Ottemöller

An earthquake sequence of more than 100 discrete earthquakes started in the Greater Manchester area of the United Kingdom on October 19, 2002. Three temporary seismograph stations were installed to supplement existing permanent stations and to better understand the relationship between the seismicity and local geology. Due to the urban location, the events were experienced by a large number of people. The largest event on October 21 had a magnitude ML 3.9. The activity appears to be an earthquake swarm, since there is no clear distinction between a main shock and aftershocks. However, most of the energy during the sequence was actually released in two earthquakes separated by a few seconds in time, on October 21 at 11:42. We applied a cross-correlation method to all events in the sequence, this showed that over 50% of the recorded events are highly correlated with at least one other earthquake in the sequence. Such events must be closely located and have a similar mechanism. We then cross-correlated the events in each group with a master event to determine consistent phase arrivals within the group. Subsequent event location shows the resultant clustering of events. We used joint hypocentral determination to simultaneously locate the swarm earthquakes, to determine station corrections and improve the relative locations between groups. This suggests that most of the events originate from a source volume of around 1-2 km and are aligned in a roughly northwest-southeast direction, dipping to the south. Source mechanisms determined for the largest of the events show strike-slip solutions along either northeast-southwest or northwest-southeast striking fault planes. The surface expression of faults in the epicentral area is generally northwest-southeast, suggesting that this is the more likely fault plane.

The Dudley Earthquake of 22 September, 2002

B. Baptie, L.Ottemöller, S.Sargeant, G Ford and A. O'Mongain

The 4.7 ML Dudley earthquake on 22 September 2002 at 23:53 (UTC) was widely felt throughout England and Wales, and was the largest earthquake to occur onshore in the United Kingdom (UK) since the magnitude 5.1 ML Bishop's Castle earthquake in 1990. The earthquake hypocentre, determined from inversion of observed P- and S-wave travel-time data, suggests a source depth of 14 km and this depth estimate is supported by forward modelling of observed waveforms. Focal mechanisms obtained from both first motion polarities of local observations and moment tensor inversion of regional observations show left-lateral, strike-slip faulting along a near vertical, near north–south striking fault plane whose orientation is in good agreement with the surface expression of the observed faults in the region. Two aftershocks were recorded within the location error ellipsoid of the mainshock. Comparison of the waveform signals revealed that the mainshock and aftershocks were nearly co-located and possibly had the same source mechanism. The observed peak ground acceleration is found to be less than that predicted using empirical relations, which have been considered applicable in the UK. Seismic moment M0 and stress drop Dr were measured from on-scale records where Lg arrivals were clear, and then used to give better estimates of the peak ground accelerations using a stochastic approach.

Earthquake Monitoring 2003/2004, BGS Seismic Monitoring and Information Service, Fifteenth Annual Report

B. Baptie, B. and L. Ottemöller, L.

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.

Macroseismic surveys in theory and practice

I. Cecić and R.M.W. Musson

Macroseismology is the part of seismology that collects and evaluates non-instrumental data on earthquakes, i.e. effects on people, objects, buildings and nature. The methods that seismologists use for collecting and evaluating the macroseismic data are often based on long (trial-and-error) experience more than on some formal procedure. Until very recently manuals or guidelines on how to do a macroseismic survey were rare and often superficial. After an earthquake is felt in some region, the data are usually collected by means of questionnaires. Field survey is an obligatory tool that complements the questionnaires in the case of a damaging earthquake. An overview of the approaches to deriving the earthquake parameters (epicentre and barycentre, epicentral intensity, magnitude, depth, source parameters) from macroseismic data, as well as a review of some existing practices is given. [This abstract also appeared in the 15th Annual Report for a previous version of this publication.]

The Dudley Earthquake Of 22 September, 2002

D. Galloway, J. Bukits and B. Baptie

The 4.7 ML Dudley earthquake on 22 September 2002 at 23:53 (UTC) was widely felt throughout England and Wales and was the largest earthquake to occur onshore in the United Kingdom (UK) since the magnitude 5.1 ML Bishop's Castle earthquake in 1990. The earthquake hypocentre, determined from inversion of observed P- and S-wave travel-time data suggests a source depth of 14 km and this depth estimate is also supported by forward modelling of observed waveforms. Focal mechanisms obtained from both first motion polarities of local observations and moment tensor inversion of regional observations show left-lateral, strike-slip faulting along a near vertical, near north-south striking fault plane whose orientation is in good agreement with the surface expression of the observed faults in the region. Two aftershocks were recorded within the location error ellipsoid of the mainshock. Comparison of the waveform signals revealed that the mainshock and aftershocks were nearly co-located and possibly had the same source mechanism. The observed peak ground acceleration is found to be less than that predicted using empirical relations, which have been considered applicable in the UK. Seismic moment and stress drop were measured from on-scale records where Lg arrivals were clear, and then used to give better estimates of the peak ground accelerations using a stochastic approach.

Slope stability issues in hydrate bearing sediments under seismic loading

P. Jackson, D. Gunn, D. Long, R.M.W. Musson, M. Lovell, J. Rees, C. Rochelle, K. Bateman, P. Hobbs and V. Nelder

While there is debate concerning total gas-hydrate reserves, researchers have suggested boundary surfaces of stable hydrates are far larger than originally anticipated. Recently, a theoretical basis has begun to emerge supporting the hypothesis that pore pressures may increase on hydrate dissociation. Therefore, re-assessment of risk (e.g. earthquake triggers) to seafloor installations is required. Typically, regional seismic assessments exclude site-scale sediment property data. Consequently, the potential for underestimating risk is significant, particularly when shear strengths are reduced by increased pore pressure. This suggests, for example, there is a need for improved geophysical and geotechnical property-models for sediment-hosted methane-hydrates. [This abstract also appeared in the 15th Annual Report for a previous version of this publication.]

Comment on “Communicating with uncertainty: A critical issue with probabilistic seismic hazard analysis”

R.M.W. Musson

In the last 30 years, seismologists have increasingly turned to probabilistic approaches with which to express hazard. Probabilistic seismic hazard analysis (PSHA) enables one to start with an a priori definition of a probability level that society can consider to be an “acceptable risk” (which will be different according to whether we are dealing with the possible collapse of a radio mast or a nuclear power-plant) and work out the level of ground shaking that has that likelihood of occurring in the lifetime of the structure. We assess subconsciously what is an “acceptable risk” every time we cross a busy street; the only difference here is that the values are formalised.

Unfortunately, many people, including scientists, have difficulty in dealing with probabilities. Scientists would rather have laws. This leads to myths and misunderstandings of probability theory that extends even to people working directly with hazard. It is remarkable to encounter complaints about a hazard value being expressed as having a return period of 10,000 years, on the grounds that in that long period of time seismicity patterns may change. In fact, nothing is being said about what will happen once in 10,000 years; it’s just an expression for the hazard value that has a 1 in 10,000 chance of happening next year.

A recent paper in Eos has the unfortunate effect of further propagating some of the myths about probabilistic seismic hazard. Given the importance of PSHA results in the planning process, it is important to have a balanced and accurate idea of what PSHA can and cannot do. The authors present four key areas in which they believe PSHA suffers from limitations, and since all four are to a greater or lesser extent illusory, they need to be refuted.

Joint solution of seismicity parameters for seismic source zones through simulation

R.M.W. Musson

A key issue in seismic hazard modelling is determining seismicity parameters for each source zone in a given model. The three main parameters are the activity rate, the b-value (slope of the Gutenberg-Richter magnitude-frequency curve), and the maximum magnitude. Procedures for estimating these vary from study to study; in recent years the application of maximum likelihood methods, with or without priors, seems to be the most favoured approach. A new approach is presented here, based on Monte Carlo methods, which solves for all three parameters simultaneously. The conceptual basis is as follows: there exists some “true” set of values for a, b and Mmax that governs the long-term occurrence of earthquakes in a zone. Take three values for a, b and Mmax at random and use them to generate a synthetic earthquake catalogue, subject to the same historical constraints as the real catalogue. Is the resulting synthetic catalogue similar to the real one? If so, the a, b and Mmax values are credible. If not, try again. If one repeats the exercise a very large number of times, one easily builds up a weighted distribution of credible values for a, b and Mmax that can be converted directly into a logic tree structure. The method is entirely data-driven, and imposes no preconceived assumptions on the shape of the uncertainty distribution. Also the method tests implicitly whether the Gutenberg-Richter model itself is credible for that data set. If it turns out to be the case that no values for a, b and Mmax can provide a good approximation to the observed data, then a different seismicity model is called for. [This abstract also appeared in the 15th Annual Report for a previous version of this publication.]

Detection Of coseismic and preseismic deformation using PSInSAR: The Iwate-Ken Nairiku-Hokubu Earthquake Of 3 September 1998

R.M.W. Musson, M. Haynes and A. Ferretti

PSInSAR is a technique for space-based remote sensing of ground deformation, using permanent scatterers to give greater accuracy of measurement than is possible with conventional InSAR techniques. A recent project involving the use of PSInSAR in northern Honshu, Japan, showed ground anomalies apparently connected with the Iwate-ken Nairiku-hokubu earthquake of 3 September 1998 (5.8 Mw); these involved both upward and downward movements at the time of the earthquake itself, and a gradual upward displacement for about two years prior to the earthquake. Both these observations are confirmed from other forms of measurement such as GPS and levelling. The preseismic deformation was indirectly related to the earthquake; it was not tectonic, but connected to volcanic activity beneath Mt Iwate. But the Iwate-ken Nairiku-hokubu earthquake is considered to be a tectonic earthquake and not a volcanic earthquake; therefore the relationship between the volcanic inflation and the 3 September 1998 earthquake is one of triggering. In this particular instance, the PSInSAR data tell us little not available from other sources (e.g. GPS, levelling, field observations). However, the confirmation of the PSInSAR results in this study is relevant to the validation of the method for use in other cases where other types of data may be lacking.

The IASPEI Working Group on Seismological Archives: a status report

R.M.W Musson, J Batllo, J Dewey and J Schweitzer

Following a decision taken by the IASPEI Commission on Seismological Observation and Interpretation at Sapporo in July 2003, the WG on Seismological Archives was set up to investigate the problems of preserving the archives of historical seismology. In many countries, the records (seismograms and bulletins) associated with the early development of seismology are under threat. Nobody likes the tedious chore of looking after piles of dusty old seismograms; as a task it hardly has the glamour of installing new networks of the very latest instruments. So, in many institutes, the will to conserve these records is eroded over time. But in fact, these old documents are still of vital importance today. The highest aim in seismology is to improve human existence through disaster mitigation. For this one needs the maximum information about past earthquakes; especially the largest ones. The largest earthquakes in any region are essentially rare events; therefore the longer one can extend earthquake catalogues back in time, the better one's understanding of the earthquake hazard. To this end, preserving the seismological records of past earthquakes, and ensuring that they are readily available to researchers, should be a key activity. The aim of this WG is firstly, to make inventories of the seismological archives that still survive (much has been lost already), and secondly, so far as possible, advise on and facilitate the preservation of existing collections, especially those under threat.

An intensity hazard map for the UK

R.M.W. Musson

Although hazard studies are more frequently conducted using physical measures of strong ground motion such as PGA, hazard studies expressed as intensity are also of value. While intensity hazard cannot be directly related to engineering design, for insurance, planning and civil defence purposes it is perhaps more useful to show hazard in terms of a parameter that expresses better the potential for damage to buildings. All that is need is to have an attenuation equation that relates intensity to magnitude and distance. A recent study in the UK, drawing on a large amount of intensity data from historical and modern earthquakes, has resulted in the establishment of a well-supported intensity attenuation equation for the UK, and this has been used to prepare an intensity hazard map for the whole UK showing the hazard at the 475-year return period level. The source model used is an evolution of that used in previous hazard mapping studies in the UK and that used for the GSHAP and SESAME projects. As the model is still under review, the map presented here is something of the way of an interim version.

Implementation of upper bounds on strong ground motion in probabilistic seismic hazard assessment

R.M.W. Musson

Given the accepted lognormal scatter found in the attenuation of strong ground motion parameters such as PGA, it is implicit that, even for moderate earthquakes, there is an infinitely small probability of observing an infinitely high ground motion when untruncated distributions of residuals are used. For this reason, standard hazard curves, when projected indefinitely to lower and lower probabilities, continue to predict higher and higher hazard values, though logically one might expect them eventually to become asymptotic to some maximum feasible value. Truncation may be applied either with respect to a given number of standard deviations of scatter, or by specifying an absolute limit, or both. Up to now, decisions made about which limits to apply have been subjective. Consensus judgement has tended to limit scatter at around 2-3 sigma values. The incorporation of such limits may require adjustment to some existing hazard software; the M3C program used by BGS was always designed to allow the application of such limits as a standard operating procedure. Indeed, the use of Monte Carlo methods as a tool for PSHA studies makes it trivially easy to implement any scheme to apply upper bounds on strong motion values. Some worked examples are presented here to demonstrate the quantitative implications of applying upper bounds in different circumstances.

Objective validation of seismic hazard source models

R.M.W. Musson

In many cases, the process of conducting probabilistic seismic hazard studies is something of a black box. A seismic source model is designed, it is fed into a seismic hazard program, and a hazard curve is the output. It does not seem to be the case that there are established formal procedures for checking that the model is a reasonable reflection of reality. Aside from obvious errors such as typing mistakes in the model file, it is easy to introduce flaws into a hazard model through design decisions that seemed proper at the time, but serve to make the model unrealistic. A simple example is the forcing of an inappropriate magnitude-recurrence model onto data that can't be fit by such a model. The hazard results at the end of the process may look "reasonable", but if they come from a model that is actually incompatible with the observed data, they cannot be considered very robust. Forward simulation provides an excellent means of testing source models in an objective way. A source model can be used to construct large numbers of synthetic earthquake catalogues, which represent different possible outcomes of the seismicity over the next 50 years. These catalogues can then be compared to the historical catalogue in terms of spatial and magnitude distribution, and various statistical tests, including the use of marked point processes, can be run to determine if the future predictions are compatible with the historical observations. If this is not the case, the model needs to be reviewed closely to determine the source of discrepancy. This paper provides some worked examples in the context of UK seismic hazard studies.

Space-based tectonic modelling in subduction areas using PSInSAR

R.M.W. Musson, M. Haynes and A. Ferretti

While the application of InSAR (Interferometric Synthetic Aperture Radar) techniques to seismology has bben well known since the mid-90s, PSInSAR is generally unfamiliar to the earth science community. The PS stands for "permanent scatterer", and it is the use of these (along with the volume of scenes employed) that distinguishes the method from more familiar InSAR techniques. A permanent scatterer is any persistently reflective pre-existing ground feature, such as building roofs, metallic structures, and even large boulders. The use of these features offers the possibility of measurements of ground displacements to a degree of accuracy, and over periods of time, previously unobtainable from conventional interferometry. Furthermore, it is possible to construct histories of displacements over the full temporal extent of the SAR data archive (started in 1991) for any part of the globe with data coverage. PSInSAR therefore represents the equivalent of a newly-discovered, super-accurate, extremely dense GPS network that has been in existence for the last twelve years.

The high resolution of PSInSAR data, coupled with its being particularly suited to urbanized areas (numerous buildings, therefore many PS points) makes it an excellent tool for studying things like urban subsidence. However, it also has applications in seismology: as a substitute for GPS data where these do not exist, and as an enhancement where they do. In this paper we report on a pilot project in Japan, the principal aim of which was to calibrate and test the PSInSAR measurements in an area where ground truth is very well established from GPS and levelling data. It is shown that PSInSAR data have the potential to be used to detect locked sections of subduction zones by means of data inversion techniques.

A critical history of British earthquakes

R.M.W. Musson

This paper reviews the history of the study of historical British earthquakes. The publication of compendia of British earthquakes goes back as early as the late 16th Century. A boost to the study of earthquakes in Britain was given in the mid 18th Century as a result of two events occurring in London in 1750 (analogous to the general increase in earthquakes in Europe five years later after the 1755 Lisbon earthquake). The 19th Century saw a number of significant studies, culminating in the work of Davison, whose book-length catalogue was published finally in 1924. After that appears a gap, until interest in the subject was renewed in the mid 1970s. The expansion of the UK nuclear programme in the 1980s led to a series of large-scale investigations of historical British earthquakes, all based almost completely on primary historical data and conducted to high standards. The catalogue published by BGS in 1994 is a synthesis of these studies, and presents a parametric catalogue in which historical earthquakes are assessed from intensity data points based on primary source material. Since 1994, revisions to parameters have been minor and new events discovered have been restricted to a few small events.

Design earthquakes in the UK

R.M.W. Musson

Three sites in the UK are taken, representative of low, medium and high hazard levels (by UK standards). For each site, the hazard value at 10-4 annual probability is computed using a generic seismic source model, and a variety of ground motion parameters: peak ground acceleration (pga), spectral acceleration at 10 Hz and 1 Hz, and intensity. Disaggregation is used to determine the nature of the earthquakes most likely to generate these hazard values. It is found that the populations are quite different according to which ground motion parameter is used. When pga is used, the result is a rather flat magnitude distribution with a tendency to low magnitude events (≤ 4.5 ML) which are probably not really hazardous. Hazard-consistent scenario earthquakes computed using intensity are found to be in the range 5.8-5.9 ML, which is more in accord with the type of earthquake that one expects to be a worst-case event in the UK.

Faulting and hazard in low seismicity areas

R.M.W. Musson

The relationship between faulting and seismicity in areas of low to moderate seismicity, such as Northern Europe, tends to be obscure. Thus, concepts in hazard analysis originating in the context of active tectonic environments such as California may not be readily applicable. A classic example is the search for “active” faults, where the standard definition of an active fault follows from that laid down by USEPA (US Environmental Protection Agency) along the lines that any fault that can be shown to have produced an earthquake in the last 10,000 years is so categorised. Although one can, and in some circumstances must, evaluate a list of local mapped faults to assess their seismic capability, there is a danger of overlooking the fact that all earthquakes must occur on some fault. Thus, in a country like the UK where around 300 events are detected every year, the number of faults that are “active” by the USEPA definition must also be in the hundreds, although one is in the position of not being able to name a single one of them with complete confidence.

The assessment of faulting and seismicity has importance in two respects to hazard for nuclear waste disposal, depending on whether one is concerned with rupture (displacement) hazard or vibratory hazard. Both issues need to be addressed; they also share some common problems. Fault displacement hazard refers to the danger of physical movement along a fault plane disrupting the waste emplacement; one can distinguish between principal fault hazard (movement along the fault plane of the earthquake) and distributed fault hazard (secondary movement at some distance from the principal fault plane). Vibratory hazard concerns the possibility of damage due to strong shaking. Secondary hazard due to seismic disruption of ground water patterns is also possible. These topics are covered in a general way in this discussion, which is relevant to a range of geological media. Considerations particularly relevant to argillaceous media are noted where they occur.

Intensity attenuation in the UK

R.M.W. Musson

Intensity attenuation is relatively little studied compared to the attenuation of peak ground acceleration, due to the fact that the PGA can be used for engineering design, while intensity cannot. However, intensity has other uses, including the estimation of effects (including damage) of future earthquakes, and hence, at least in a general way, the study of earthquake risk. Knowledge of intensity attenuation is also useful in calibrating hazard models against historical experience. In this study, the attenuation of intensity in the UK is thoroughly evaluated from a data set comprising 727 isoseismals from 326 British earthquakes, including both modern and historical events. Best results are obtained by restricting the data set to events contributing at least two isoseismals. The preferred equation is

$$I = 3.31 + 1.28\ ML - 1.22 \ln R$$

where I is intensity (European Macroseismic Scale), ML is local magnitude, and R is hypocentral distance. The sigma (uncertainty) value is 0.46. Some sample applications of this formula are demonstrated.

Undead earthquakes

R.M.W. Musson

This paper deals with the problem of fake earthquakes that keep returning into circulation. They “walk again” like the undead of horror fiction. The particular events discussed are some very early earthquakes supposed to have occurred in the UK, which all originate from a single enigmatic 18th century source.

An Unusual Earthquake Sequence In The Highland Boundary Fault Zone, Aberfoyle, Scotland, 2003

L. Ottemöller

Major tectonic boundaries in the UK have not shown significant seismic activity as may be expected and could be observed with the installation of modern seismograph networks since the 1970s. The Highland Boundary Fault Zone (HBFZ) is one of these structures cutting across Central Scotland. In historic times seismicity had occurred in this zone around Comrie, however, an earthquake sequence in 2003 near Aberfoyle was the first significant activity recorded on modern instruments. This study describes detailed analysis of these data. Waveform signals between events were almost identical and applying a cross-correlation technique combined with joint hypocentre determination, it was possible to resolve the alignment of events in WSW-ENE direction. This alignment matched one of the nodal planes determined in a joint focal mechanism. The fault plane was dipping to the northwest, and showed oblique sinistral strike slip and normal movement. The orientation agrees with direction and orientation of features in the HBFZ. It was concluded that the WSW-ENE striking nodal plane was the causative fault that is associated with the HBFZ. 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. Slip direction was not as expected from the regional stress pattern, and it was concluded that the events presented local stress adjustment, rather than an indication of significant movement in the HBFZ.

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. (subject to approval by ConocoPhillips and partners)

Attenuation of PGA from small UK earthquakes

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

In low seismicity regions where earthquakes with engineering significance are infrequent, seismic hazard assessments often rely on the results of relations developed elsewhere that are deemed appropriate and/or stochastic modelling, to estimate ground motion. This can make a significant contribution to the uncertainty associated with the final results. In the UK, there are a large number of peak ground acceleration (PGA) observations from small earthquakes (ML < 4). In an effort to reduce, or at least understand some of the uncertainty associated with seismic hazard results in the UK, empirical relations for estimating PGA were developed using these data. Relations were derived for both horizontal and vertical PGA, and ML and Mw using recordings made up to 300 km from the hypocentre (ML £ 4.1). Two stage regressions were used because distance and magnitude were strongly correlated in both data sets and the functional form of the relations contained a non-linear magnitude term. For ML, s is around 0.7 (in natural logs) for both the horizontal and vertical components. s is greater than 0.9 for Mw because of the additional uncertainty in the relation used to convert from ML to Mw. The relations compare well with PGA observations from small earthquakes in the Umbria-Marche sequence as well as larger earthquakes (ML > 5) in southern Europe. This suggests that high frequency attenuation in the UK is comparable to tectonically active regions. Furthermore, the results indicate that it may be valid to extrapolate a relation based on PGA observations from small earthquakes to larger magnitudes, provided the magnitude transition is understood.

Subduction zones with potential for PSInSAR investigation for space-based disaster reduction

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

The so-called ABIC (Akaike's Bayesian Information Criterion) method has been used successfully in an number of studies in Japan to invert deformation data, principally from intensive levelling studies but also from GPS, in order to image the locked area in subduction fronts. Elsewhere the technique has met with mixed success, partly due to issues of data availability. The use of PSInSAR (Point Scatterer Interferometric Synthetic Aperture Radar) opens up the possibility of obtaining dense data coverage of very accurate displacement measurements over a roughly ten-year period (the data archive starts in 1992). Given sufficient commitment, studies could be launched in a number of areas that would potentially show the extent to which subduction zones are locked, and where the next great earthquake is likely to nucleate. This report examines and describes the world's major subduction zones and assesses their suitability for imaging using PSInSAR and ABIC. Some zones are likely to be unsuitable because the permanent scatterers used by PSInSAR are generally large buildings; thus one would have poor data coverage in Alaska. Other zones, such as the Cascadia subduction zone in the Pacific Northwest in North America should be excellent candidates.

Lg-wave attenuation in the UK

S. Sargeant, L. Ottemöller and R. Musson

The UK is classified as a stable continental region (SCR) and in the absence of any UK-specific estimates, attenuation has been assumed to be similar to SCRs like Scandinavia and eastern North America. Now that there are sufficient data, the validity of this assumption was tested. To do this, vertical recordings of Lg-waves from 11 larger (3.4 to 4.7 ML) UK earthquakes were used. The efficiency of Lg-wave propagation (defined as the spectral amplitude ratio of Lg to Pn) was measured for a range of frequencies. For most paths, the spectral amplitude of Lg was less than six times larger than that of Pn. Only these records were used to investigate attenuation. Q(f) (the quality factor) was found by simultaneously inverting for the source, path and site effects for a range of frequencies, using Lg recordings made at epicentral distances greater than 200 km. The uncertainties on the results are large, particularly at lower frequencies but show that at frequencies of less than 4 Hz, Q is roughly constant and comparable to other SCRs. Above 4 Hz, Q is strongly frequency dependent and comparable to estimates for western Central America and California. This result could be used in conjunction with ongoing stochastic ground motion modelling in the UK and may influence which empirical ground motion prediction relations are chosen for UK-specific seismic hazard assessments.

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B.A. Simpson (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 2004 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.