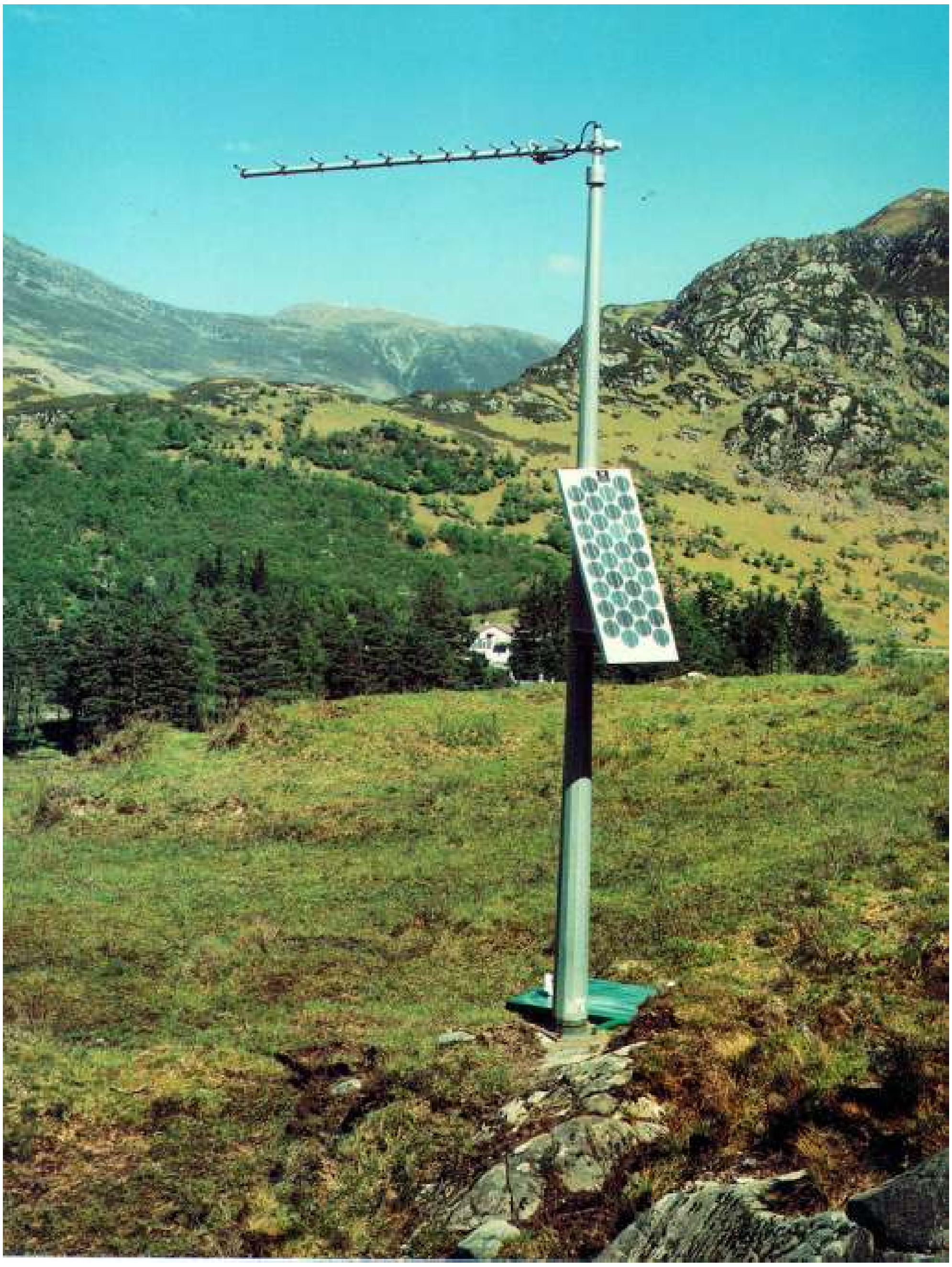
UK EARTHQUAKE MONITORING 2002/2003

BGS Seismic Monitoring and Information Service

Fourteenth Annual Report



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BRITISH GEOLOGICAL SURVEY

TECHNICAL REPORT IR/03/67

UK Earthquake Monitoring 2002/2003

BGS Seismic Monitoring and Information Service

Fourteenth Annual Report

Alice Walker, Brian Baptie and Lars Ottemöller

June 2003

UK Seismic Monitoring and Information Service Year Fourteen Report to Customer Group: June 2003

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Solar-powered earthquake-monitoring station in the north-west Highlands of Scotland (T Bain)

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BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available through the Sales Desks at Keyworth and at Murchison House, Edinburgh, and in the BGS London Information Office in the Natural History Museum Earth Galleries. The adjacent bookshop stocks the more popular books for sale over the counter. Most BGS books and reports are listed in HMSO's Sectional List 45, and can be bought from HMSO and through HMSO agents and retailers. Maps are listed in the BGS Map Catalogue, and can be bought from BGS approved stockists and agents as well as direct from BGS.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British Technical aid in geology in developing countries as arranged by the Overseas Development Administration.

The British Geological Survey is a component body of the Natural Environment Research Council

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UK EARTHQUAKE MONITORING 2002/2003

1. Executive 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) 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). This Customer Group is listed in Annex A.

In the 14th year of the project (April 2002 to March 2003), three subnetworks were upgraded with the installation of data loggers running under the QNX operating system, and a strong motion instrument was installed at Hartland in North Devon. The increasing number of acceleration records being captured by strong motion instruments, is feeding into a better understanding of attenuation and seismic hazard in the UK.

Some 235 earthquakes were located by the monitoring network in 2002, with 87 of them having magnitudes of 2.0 ML or greater (Annex B). A total of 42 events in this magnitude category were reported as felt along with 6 smaller ones. Nine strong-motion records were captured from six of the nineteen sites now equipped with strong motion instruments. The largest earthquake in the reporting year, with a magnitude of 4.7 ML, occurred near Dudley on 22 September. It was felt up to 337 km away and over an area of 126,000 km^2 (Isoseismal 3 EMS) and reached a maximum intensity of 5 on the European Macroseismic Scale (EMS, Annex H). A peak ground acceleration of 153 mms^{-2} was recorded on the three-component accelerometer at Keyworth, a distance of 83 km from the epicentre. The focal mechanism indicates strike slip movement along near vertical fault planes striking either NNE-SSW or WNW-ESE. The following month, an earthquake sequence commenced near Manchester with 117 events located, 37 of which were felt by the local population. The sequence caused widespread alarm in the greater Manchester area. The largest offshore earthquake occurred in the central North Sea on 12 October 2002 with a magnitude of 3.5 ML, approximately 70 km east of the Shetland Islands. In addition to earthquakes, BGS frequently receives reports of seismic events felt and heard, which on investigation prove to be sonic booms, spurious or in coalfield areas, where much of the activity is probably induced by mining. During the reporting period, data from six sonic events were processed and reported upon following public concern or media attention.

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, 2003). In all these reporting areas, scheduled targets have been met or surpassed.

Maintenance and protection of historical archives, another primary goal of the project, has continued and has been enhanced by donations of the Soil Mechanics UK data, from a study in the early 1980's and the British Association for the Advancement of Science Seismological Committee archives.

The environmental monitoring stations at Eskdalemuir and Hartland observatories recorded a variety of parameters throughout the year and the data are now accessible on-line through an Internet connection.

2. Introduction

The UK earthquake 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 current supporters of the programme, drawn from industry and central and local Government, are referred to as the Customer Group, and are listed in Annex A. The project started in April 1989, building on small networks of seismograph stations which had been installed previously for site-specific purposes. There is now UK-wide coverage.

Background earthquake monitoring is required to refine our understanding of the level of seismic risk in the UK. Although seismic hazard/risk is low by world standards it is by no means negligible, particularly with respect to potentially hazardous installations and sensitive structures. The 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, objective information is also provided to verify the nature of seismic events or to confirm false alarms, which might result from locally generated instrument triggers. In addition, seismic events cause public concern and there is a need for objective information as soon as possible in order to allay any unnecessary concerns. Most seismic events occur naturally but some are triggered by human activities such as mining, and other tremors (eg. sonic booms and explosions) are often mistaken for earthquakes. The information service aims to rapidly identify these various sources and causes of seismic events which are felt or heard.

To improve the capacity of the network to deliver on-scale data for larger earthquakes, and to more effectively calculate their magnitudes, strong motion instruments have been integrated with the high sensitivity network. A broadband station at Edinburgh, which is capable of recording a much wider spectrum of frequencies, and which has improved signal quality, is important in the wider monitoring programmes across Europe and globally. It provides data through a French satellite system to the European Mediterranean Seismological Centre (EMSC) where, together with rapidly linked short-period data from three subnetworks of the UK system, it contributes to the wider European capability of providing alerts within two hours for earthquakes having magnitudes greater than 5.0.

This Year 14 report to the Customer Group, highlights the significant seismic events in the reporting period, April 2002 to March 2003. The catalogue of earthquakes for the whole of 2002 is plotted to reflect the period for which revised data are available and to be consistent with the annual bulletin, which is produced as a separate volume. An updated map of epicentres since 1979 is also included for earthquakes with magnitudes ≥2.5 ML; the threshold above which the data set is probably complete. Such events are normally felt by people.

3. Programme objectives

The overall objectives of the service were established in 1988/89 and have been extended by the Customer Group as technology and resources have permitted. They are:

- To provide a database for seismic risk assessment using existing information together with that obtained from a uniform distribution of modern seismograph stations throughout onshore UK capable of detecting and locating all earthquakes with magnitudes ≥ 2.5 ML.

- To enhance the data through historical research and capture of additional data by deployment of temporary stations.

- To maintain, and make widely available, the database and archive of seismicity and seismic records.

- To provide near-immediate preliminary responses to reports of seismic vibrations, heard or felt, or of other significance to the Customer Group.

- To ensure this rapid response by providing a 24-hour on-call service operated by experienced seismic analysts.

- To conduct macroseismic surveys of felt/damaging effects for significant events as appropriate.

- To provide the information on a web-site for passive access, and to be responsive through provision of statements to the press and in radio and television interviews.

- To publish, annually, bulletins of seismic parameters, and progress reports, and, at five-yearly intervals, an updated map of seismicity since 1980.

- To develop a strong motion capability within the network to enable maximum ground accelerations to be captured on-scale by instruments close to small earthquakes and, by instruments sited over a wide area for the rare larger ones.

- To upgrade the capability of the network following advances in technology, as funding permits.

- To provide the capability to monitor a range of environmental parameters in order to attract broader customer support.

4. Summary of achievements since 1989

Improvements in network coverage, event detection, delivery of information, databasing and archiving have been made during the course of the project. Highlights are outlined below:

4.1 UK Network

- The UK seismic monitoring network has grown to 146 stations with an average spacing of 70 km.
- Improvements have been made to earthquake detection and location capability, with all onshore magnitude 2.5 earthquakes located, even in poor noise conditions.
- The transition from analogue to digital recording has been made with benefits to data analysis, interpretation and speed of dissemination. Upgrades to faster modem links and larger disk buffers have been made as technology has advanced and costs reduced.
- All UK station positions have been resurveyed using GPS techniques.
- Nineteen strong motion accelerometers have been installed across the UK, from Shetland to Jersey, including four stations specifically commissioned by British Energy, MOD and the Jersey New Waterworks Company.
- A broadband station installed at Edinburgh has improved the quality of data from distant earthquakes and has added to the value of data exchange with neighbouring countries.
- The potential for using the seismic network for multifunctional environmental monitoring has been proved and a full demonstration system has been established at the BGS Eskdalemuir Observatory using twenty environmental parameters interfaced with the seismic data transmission system.

4.2 Seismic Data

- In order to improve the study of seismicity in the UK's offshore areas, strong data exchange links have been established with European neighbours and with several international agencies: EMSC (European Mediterranean Seismological Centre, Paris), the ORFEUS data centre (KNMI, De Bilt, the Netherlands) and ISC (International Seismological Centre, Newbury). To enhance these links, BGS coordinated a 10-nation data exchange network (the Transfrontier Group) from Denmark to Portugal, under the EU natural hazards programme.
- Historical material from former UK seismic stations has been brought together and housed in a National Seismological Archive at the BGS laboratories in Edinburgh. A watching brief has been kept on archives held elsewhere to prevent their dispersal or destruction and some have been transferred to Edinburgh as a result. A series of reports has been made available on-line.

- The World Seismological Bulletin collection database has been published and is available on the Internet. A UK historical seismological observatories report has been compiled and is also available on the Internet.

- UK earthquake data from earlier analogue systems, held on ½" FM magnetic tapes, have been extracted and digitised for events with magnitudes ≥2.0 since 1977.

- The seismicity database is held in a readily accessible format (both for parameter and waveform data) and is updated continuously. Back-up copies are held outside the BGS building in a commercial facility. In 2003, the UK seismicity database (both historical and instrumental) was made available to members of the Customer Group on CD. It is also available on the web at (www.earthquakes.bgs.ac.uk).

- An improved catalogue of historical UK earthquake information has been combined with the modern instrumental data to provide the input for two seismic hazard mapping studies. The assessment for the offshore region was published in 1997 as a Health and Safety Division Offshore Technology Report, and the onshore study has been peer reviewed and published in scientific journals (Musson and Winter, 1997, and Musson, 1997). Data has been provided for a further study, to be completed this year, which will advance the understanding of seismic attenuation in the UK.

4.3 Information Dissemination

It is a requirement of the information service that objective data and information be distributed rapidly and effectively after an event, with the databases also available in the longer term. This part of the service has taken full advantage of advances in technology. It has achieved the following routes to wide dissemination:

- Immediately following a significant seismic event, the 24-hr on-call team (Annex C) is alerted and within 1-2 hours starts to answer telephone enquiries from authorities, the public and the media.

- Preliminary information (earthquake parameters, initial felt or damage reports, and the historical setting) is provided in an e-mail to Customer Group members around two hours following the event. Formerly, this was achieved by fax.

- The same information, for global destructive earthquakes only, is provided to the Red Cross, Department for International Development (DFID) and rescue services.

- Revised information is distributed over the next 24 hours to the organisations and individuals, above, as appropriate.

- Information from the database and through special studies is made widely available through the various "Public Understanding of Science" routes outlined below, and through reports and papers representing the end products of these studies (Annexes D and E).

- On the web-site (www.earthquakes.bgs.ac.uk), a seismic alert bulletin is posted shortly after the first e-mails are sent to the Customer Group. Subsequently, updates are posted and, ultimately, each new event is added to the growing database of historical and recent information now available, on the web-site, for passive access.

- Members of the public are invited to contribute directly to the study of an earthquake by providing their own experience of it, using a form on the web site. This raises their interest in the event and the results. The resulting macroseismic surveys of felt effects and damage are posted on the website.

- Annually, the earthquake parameter bulletin is published for the Customer Group (now on CD) and is also made available to other professionals. The annual progress report is also made widely available.

- At 5-yearly intervals, the seismicity map of the UK showing epicentres since 1980 (from when the data is complete for onshore events ≥ 2.5 ML) is published.

- CDs containing the historical and instrumental database, the booklet (see below), the annual bulletins and progress reports, together with PowerPoint presentations made by the project team, have been distributed to Customer Group members for their information and use.

4.4 Public Understanding of Science

- A booklet, first produced in 2000 as an intelligent lay persons' guide, has been updated and distributed throughout the country to provide details of recent earthquakes and simple explanations of terms used in seismology. It is available for download at www.earthquakes.bgs.ac.uk or by contacting the Seismology Team on 0131-667-1000.

- The booklet and other material, often on specific earthquakes, are frequently provided to schools and individual enquirers.

- In response to significant UK and global earthquakes, the project team engages with the press, radio and television. As a result, its information and scientific assessments have been widely reported. At times, the team is also involved in science feature programmes, some of which are directly targeted towards the education sector.

- Publicity brings many requests for talks to local groups; some from professional engineers and scientists but frequently from amateur associations. Most of these requests have been met.

5. Seismic activity in Year 14

5.1 Overview

The details of all earthquakes, felt explosions and sonic booms detected by the network have been published in monthly bulletins and, after final revision, in the BGS bulletin for 2002 published and distributed in May 2003 (Simpson, 2003).

A map of the 235 events located in 2002 is reproduced here as Figure 1 and a catalogue of the 87 events with magnitudes of 2.0 or greater is given in Annex B. Forty two events in that magnitude category, together with six smaller ones, are known to have been felt.

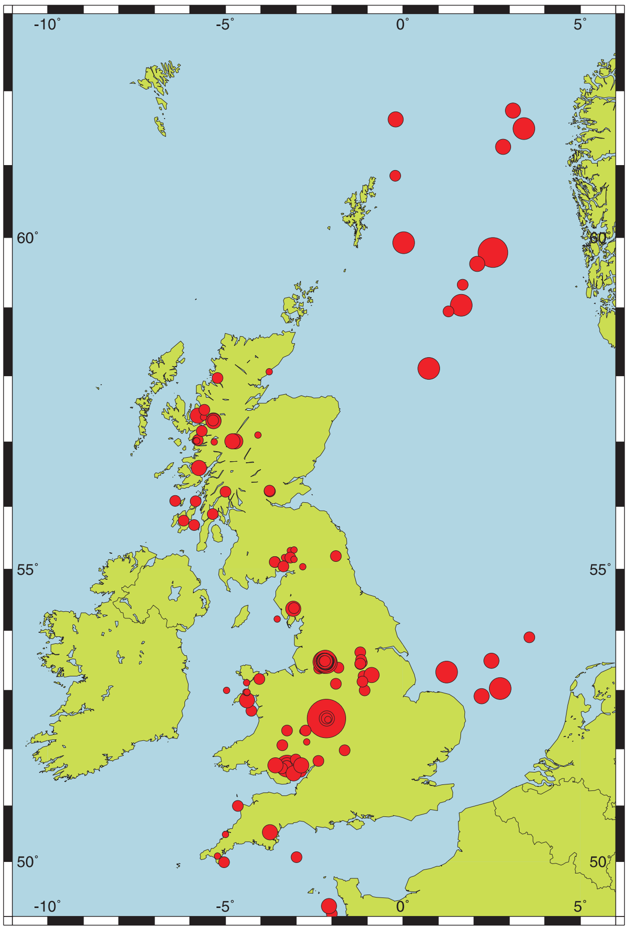

Figure 1. Epicentres of all UK earthquakes located in 2002.

Spatially, the distribution of seismicity in 2002 was similar to that of previous years with the majority of earthquakes occurring in and around Wales (especially south Wales), the Midlands, the Borders, and in western Scotland. Some activity occurred around the Channel Islands and in the northern and southern North Sea. No events were recorded in south-eastern England, Ireland, Aberdeenshire (Scotland) and the Outer Hebrides. Historically, south-eastern England has been active but Ireland and north-eastern Scotland have rarely experienced events in the past. The largest onshore earthquake during 2002 was the 4.7 ML Dudley event on 22 September. Also significant was the Manchester earthquake sequence in October and November. To date, 117 of these events have been located, with magnitudes between 1.3 to 3.9 ML, and many more have been recorded on the three temporary stations deployed close to the epicentres. Other smaller clusters of events during the year occurred near Blackford, Shiel Bridge and Mallaig in Scotland and Bargoed in south Wales.

In the period over which BGS has built up its modern seismic monitoring network in the UK (1979 to March 2003), almost all of the earthquakes with magnitudes ≥2.5 ML are believed to have been detected. The distribution of such events for that period (Figure 2) is, therefore, largely unbiased by the distribution of seismic monitoring stations for the onshore region. The accuracy of individual locations, however, will vary across the country and with time.

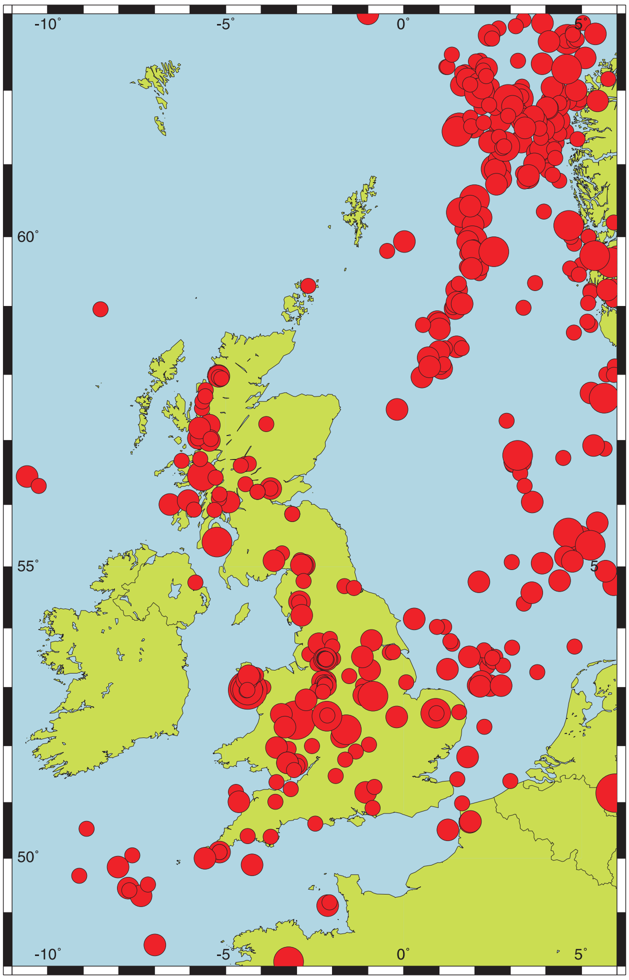

Figure 2. Epicentres of earthquakes with magnitudes 2.5 ML or greater, for the period 1979 to March 2003.

5.2 Dudley Earthquake 22 September 2002

The 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 UK since the Bishop's Castle earthquake in 1990. The hypocentre was determined based on a total of 54 phase readings identified from the seismograms recorded on the stations of the BGS seismic network. The epicentre was about 3 km northwest of Dudley and occurred at a depth of 14 km below the surface. The magnitude of 4.7 ML was determined from amplitude readings at nine seismograph stations in the distance range 80 to 295 km and at a range of azimuths. An accelerogram of the event recorded on the three nearest accelerometer stations is shown in Figure 3.

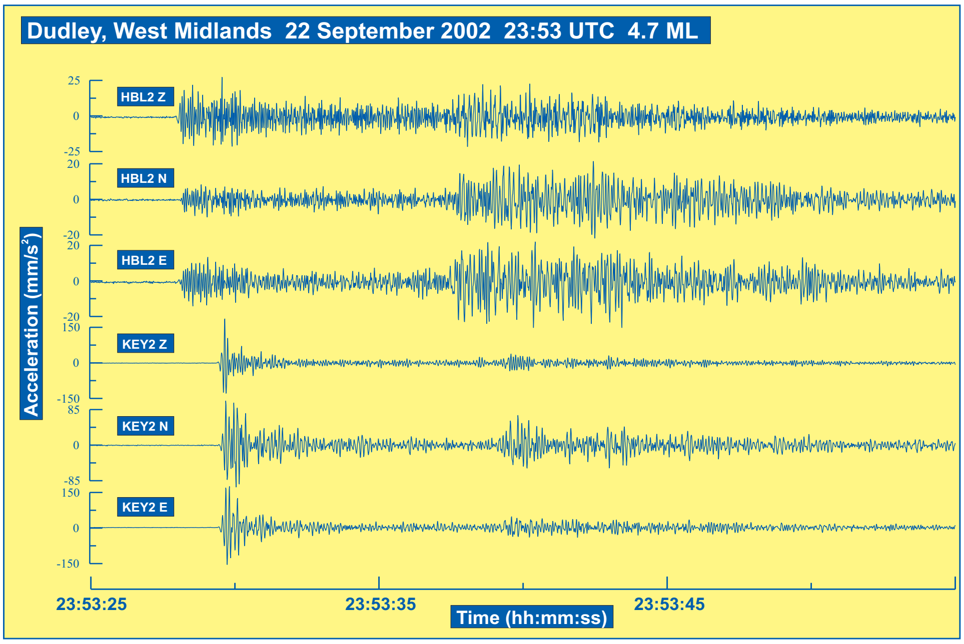

Figure 3. Accelerograms recorded from the Dudley earthquake, 22 September 2002.

The peak ground acceleration values measured for the Dudley event are listed in Table 1. The highest acceleration of 153 mms^{-2} was measured on the vertical component at station KEY2 (Keyworth, Nottingham, distance 83 km). At a similar distance (80 km), the instruments at HBL2 (Bonnylands, Hereford) recorded 22 mms^{-2} on the vertical component. The difference between the two sites is probably explained by site and path effects. Horizontal peak ground acceleration values at KEY2 and HBL2 were 56 mms^{-2} and 21 mms^{-2}, respectively, and thus lower than the values measured on the vertical components. At other sites, the measured values were observed to decay exponentially with increasing distance.

Earthquakes with the size of the Dudley event typically occur somewhere in the UK once in eight years. Comparable events, with respect to magnitude, have occurred near Carlisle in 1979, Skipton in 1944, North Wales in 1940, Ludlow in 1926 and Caernarvon in 1903 amongst others. Historically, the West Midlands area has been relatively active. The largest earthquake in the area in the last hundred years was the 15 August 1926, 4.8 ML, event near Ludlow, some 41 km away. It caused slight damage, mostly to chimneys in the epicentral area. Another prominent earthquake in the area was the 14 January 1916, magnitude 4.6 ML, event near Stafford about 36 km from Dudley.

A study was carried out after the event to investigate the macroseismic effects (Figure 4). A total of 8,400 responses to the questionnaire published in a national newspaper and on the BGS web-site were received; 6,500 from the latter. This information was analysed in detail to assign macroseismic intensity values to locations where the event was reported felt. Isoseismal contour lines were identified after plotting these data on a map. The highest isoseismal of intensity which could be plotted was 5 EMS (European Macroseismic Scale), observed over an area around Dudley, Birmingham, Walsall and Wolverhampton, and as far

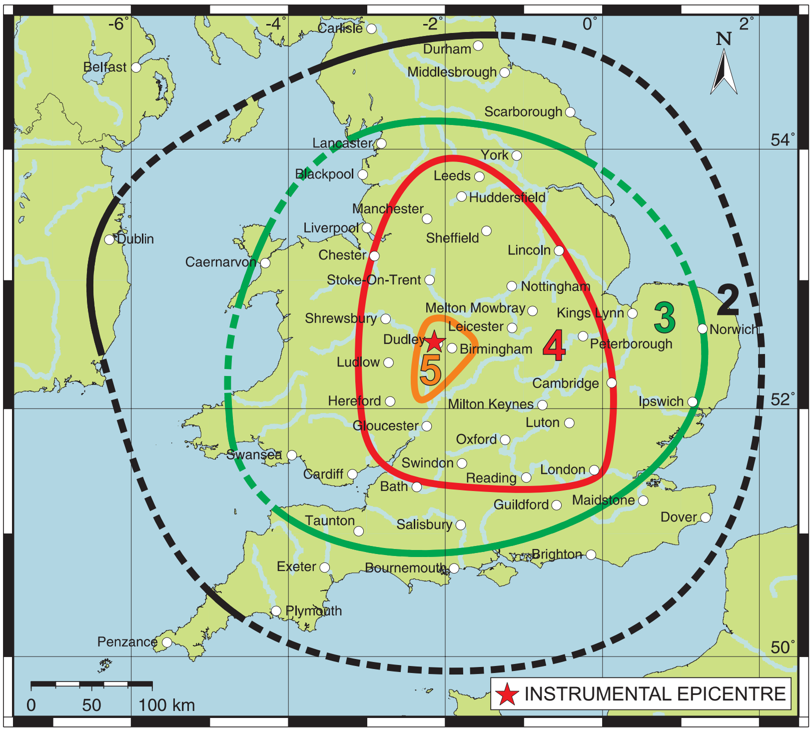

Figure 4. Macroseismic map showing the felt effects of the Dudley earthquake – EMS intensities.

south as Kidderminster and Bromwich. Locally, there were isolated examples of minor damage indicating the threshold of intensity 6 EMS (Figure 5). On a larger scale, the earthquake was felt throughout England and Wales, with the most distant reports coming from Durham in the north, and Truro, Cornwall, in the south. There were also some reports from east coast towns in Ireland. The felt area was 126,000 km^2 (Isoseismal 3). The intense public interest immediately following the event is illustrated by the dramatic increase in hits on the BGS earthquake web site; up from a background of 3,000 hits per day to 366,000 on the day of the earthquake (27,700 visitors).

Figure 5. Damage to chimney observed after the Dudley earthquake.
Photograph courtesy of PA Photos, London.

The source mechanism of the event was determined by two different methods: BGS carried out a focal mechanism analysis based on first motion polarities from locally recorded data in the UK; the Swiss Seismological Survey determined a moment tensor solution based on waveform inversion of regional broadband recordings in the UK and across Europe (Bernardi et al., 2002). Both solutions were very similar and show a strike-slip mechanism along either a NNE-SSW or WNW-ESE fault. However, the direction of dip given by each method is slightly different. The first motion polarities show either left lateral strike slip motion on a NNE-SSW fault, dipping to the east, or right lateral strike slip motion on an WNW-ESE fault dipping to the north. The moment tensor solution (from the broadband study) shows either left lateral strike slip motion on a NNE-SSW fault, dipping to the west, or right lateral strike slip motion on an WNW-ESE fault dipping to the south.

The epicentre lies in a major zone of faulting associated with the Western Boundary Fault of the South Staffordshire coalfield. It seems likely that movement on a fault, or faults, associated with this major crustal fracture could have caused the earthquake. The surface trace of the Western Boundary Fault passes to the west of Dudley and to the east of Stourbridge along a southerly or south-easterly trend. The fault throws down Triassic rocks to the west against older (Upper Carboniferous rocks) of the South Staffordshire Coalfield to the east. The epicentre was estimated at a depth of 14 km and about 1 km to the west of the surface expression of the Western Boundary Fault. The horizontal error in epicentre determination is of the order of 2 km, which means that there are possibly several faults that may have been the source of the event. The majority of the larger faults trend NE-SW, which may indicate that the NNE-SSW nodal plane is likely to be the fault plane of the earthquake. The moment tensor solution indicates a westward dipping fault plane, which agrees with the westward dip of the Western Boundary fault. However, it is possible that slip occurred on a fault splay, rather than on the main structure mapped at surface, which could accommodate other directions of dip. In addition, it is unknown how the faults continue at depth, which makes the interpretation even more uncertain.

Two aftershocks were recorded, the first on 23 September at 03:32 (2.7 ML) about 3.5 hours after the mainshock and the second some 30 hours later on 24 September at 09:29 (1.2 ML). Both these events were located within the error ellipse of the main shock. Recordings of the aftershocks were unsaturated, which allowed direct comparison of the waveform signals for both events at the same station. It appears that the signals for the first P arrival are nearly identical between the two aftershocks, indicating that the hypocentre locations of both events must be within tens of meters. An interesting observation for the first aftershock is that the first P arrival, after about 0.3 seconds, is followed by a larger signal that is identical to the first arriving phase. Considering that this phase is not seen for the second aftershock, it is possible that the first onset seen for the first aftershock is the initiation of the rupture, which was then followed by the significantly larger event. Direct comparison between the mainshock and the first aftershock was only possible for few stations at relatively large distances. These observations indicate a high degree of similarity between the mainshock and the first aftershock. It is thus likely that the 3 earthquakes originated from a small source volume and may represent rupture along the same fault.

5.3 Manchester Swarm Activity, October-November 2002

An earthquake sequence started in the Greater Manchester area on 19 October, 2002. This continued until January 2003 with more than 150 detectable earthquakes, of which 117 have been located. Fifty-three of them had magnitudes of 2.0 ML or above and thirty-seven were felt. Due to the urban location, the earthquakes were felt by a large number of people among whom there was concern because of the duration of the activity; the largest was felt up to 50 km away and caused minor damage near its epicentre. The BGS web site was once again inundated with people wanting information on the earthquakes. Interest from Dudley had barely fallen to the background level of 3,000 hits a day when it shot up to over 100,000 for the next five working days. Over the next month some 1.3 million hits were registered with a cycle picking out the working week (Figure 6) when most people have access to computers. There were 155,000 visitors to the site between 21 October and 30 November 2002.

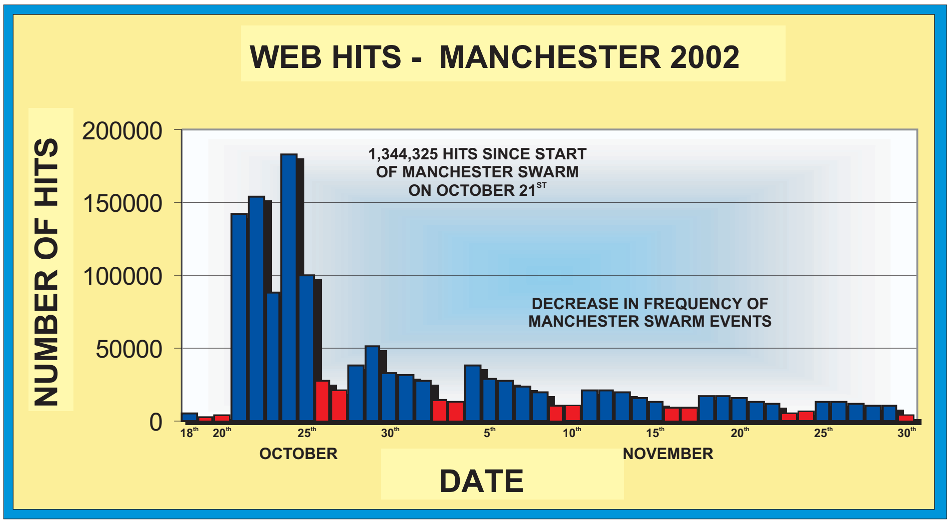

Figure 6. Access statistics for the seismology web pages from 18 October to 30 November.

The clustering in time (Figure 7) and space suggests that there is a causal relationship between the events of the sequence. The largest had a magnitude of 3.9 ML and most of the energy during the sequence was actually released by this event on 21 October at 11:42 UTC. The number of events as a function of time increased fastest in the period 21 October to 24 October, with the peak number of events occurring on 24 October. After this, the activity slowed down significantly. The Manchester area has shown little historical earthquake activity and an earthquake sequence of this type is unprecedented. However, there are other examples of earthquake swarm activity in the UK including Comrie (1788-1801, 1839-46), Glenalmond (1970-72), Doune (1997) and Blackford (1997-98, 2000-01) in central Scotland, Constantine (1981, 1986, 1992-4) in Cornwall, Johnstonbridge (mid1980s) and Dumfries (1991,1999). The largest onshore UK earthquake in decades, the 5.4 ML Lleyn event in 1984, was followed by an aftershock sequence that continued for over a year.

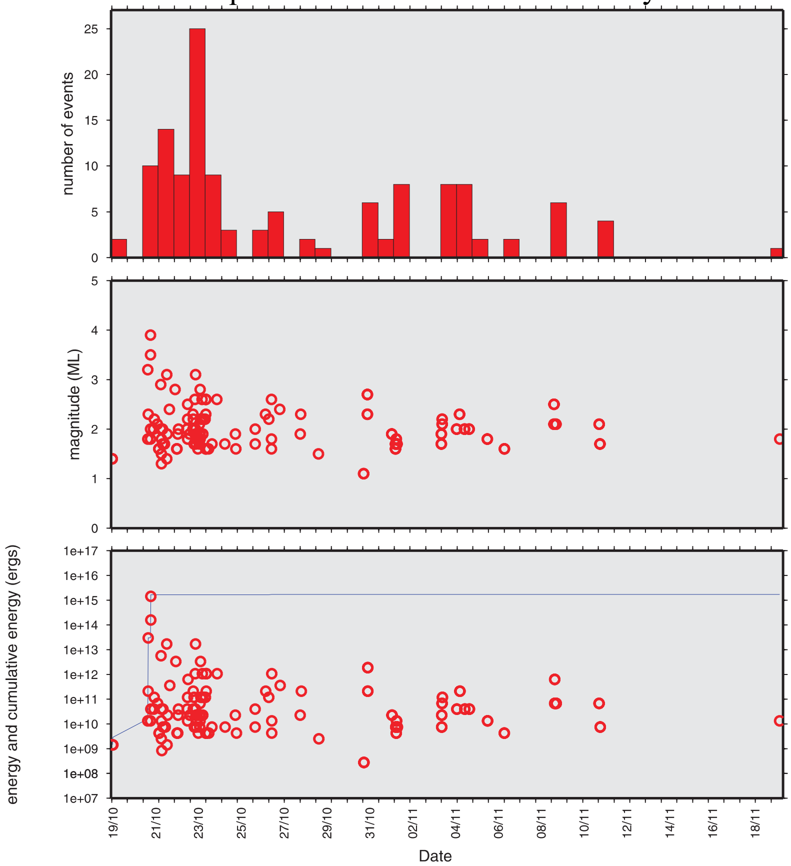

Figure 7. Event statistics for the period 19 October to 19 November showing the distribution of events with time (top). Also shown are the magnitude distribution (middle), energy and cumulative energy release (bottom).

To improve the hypocentral resolution, three temporary recording stations were deployed in the Greater Manchester area within 15 km of the epicentres. The hypocentres were found to be within a source volume of a few kilometres with shallow depths, at 1 to 3 km. However, uncertainties in the epicentre location and earthquake depth are of the order of a few kilometres, which makes it difficult to relate the earthquakes to specific faults. A seismogram of an event on 21 October (Figure 8) shows surface waves which indicates that the event occurred at a shallow depth. Joint Hypocentre Determination (JHD) has been used successfully in a number of cases, (eg. Pujol, 2000) to improve the relative locations of earthquakes and to account for lateral variations neglected in 1-D velocity models. The computer program VELEST (Kissling et al., 1994) was used to apply the JHD technique to the Manchester earthquakes, and this resulted in some increased clustering of events in the epicentral area. However, the resolution of the data is still probably insufficient to precisely image geological features.

Geologically, the Manchester and Salford area straddles the southern part of the Carboniferous, South Lancashire Coalfield and the northern part of the Permo-Triassic Cheshire Basin. The coalfield has been extensively worked from numerous collieries in the north Manchester city area. Coal mining ceased in this part of the coalfield in the late 1970s and focal depths are significantly deeper than the deepest mine workings; therefore, mine collapse can be ruled out as a cause for these events although stress adjustments over the long period of extraction may have been a contributing factor. The main faults in the epicentral area strike roughly NW-SE and dip gently to the NE. Focal mechanisms obtained for the largest of the Manchester earthquakes generally show strike-slip solutions but the strike and dip of the fault planes do not provide a good match to the faulting observed at the surface. Seismograms recorded at the closest station show significant differences between events, suggesting that the earthquakes may have resulted from displacements along a number of small faults within the hypocentral region.

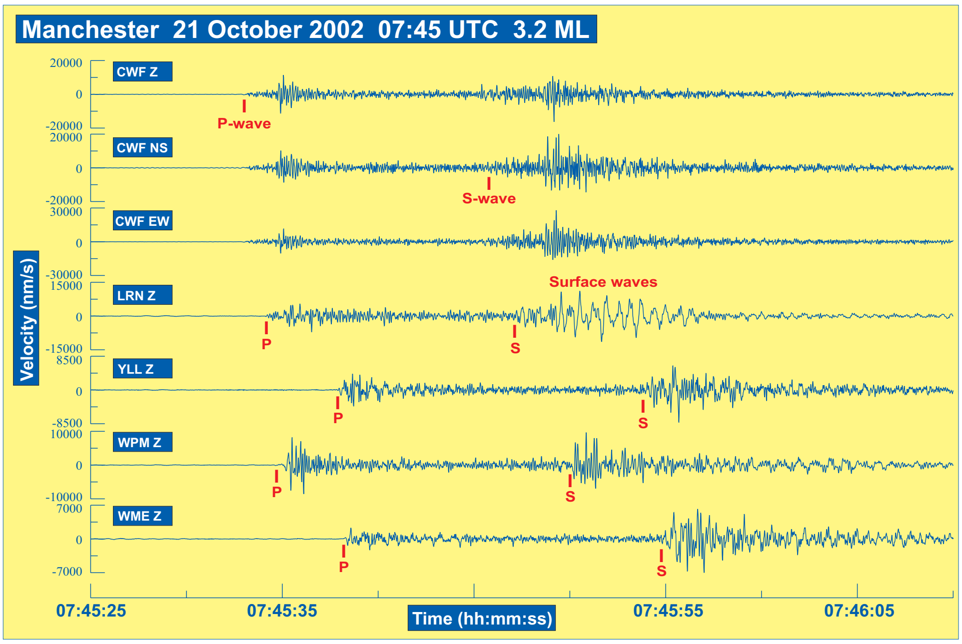

Figure 8. Seismograms of ground velocity recorded from the magnitude 3.2 ML event at 07:45 on 21 October 2002 in Greater Manchester

5.4 Cardiff earthquake 20 June 2002

A magnitude 2.9 ML earthquake occurred on 20 June near Cardiff, south Glamorgan. Felt reports were received from residents of Cardiff and Caerphilly where intensities reached 3 EMS. Felt reports included “the furniture moved” and “both the chairs moved for a few seconds”. This is an area that has experienced significant events in the past; most notably in 1974, when two earthquakes, with magnitudes of 3.9 and 4.1 ML on 25 February, caused minor damage to chimneys and roofs in Cwmbran and Newport, Gwent.

5.5 Offshore Earthquakes

The largest offshore earthquake recorded during the period, with a magnitude of 3.5 ML occurred in the Northern North Sea on 12 October 2002, with a location approximately 70 km east of Shetland. A further 12 events occurred in the North Sea and surrounding waters during the year, with magnitudes ranging between 1.5 and 3.4 ML. The largest event in the Central North Sea area, with a magnitude of 3.3 ML, was on 25 August 2002, with a location 225 km northeast of Edinburgh The largest event in the Southern North Sea area, with a magnitude of 3.1 ML, was on 22 November 2002, with a location approximately 200 km east of Grimsby.

5.6 Man-Made events

There are many man-made seismic events which people feel like earthquakes, and need to be identified; including quarry blasts, underwater explosions and sonic booms. Quarry blasts usually have characteristic waveforms, with compressional P-wave onsets (upward movement on the seismogram), low S-wave energy and pronounced surface waves, due to their near surface origin. The time of occurrence also provides further evidence as blasting is not usually allowed outside normal working hours or at weekends. Underwater explosions take two forms: WWII mines, which have been trawled up by fisherman and need to be disposed of, and weapons testing. In both cases, they can be felt by local residents and can occur at any time of the day or night. They are easy to identify on the BGS network as they produce a monotonic (single frequency) signal due to an oscillating bubble pulse which reverberates in the water column.

Activity in coalfield areas has been declining owing to the closure of coal mines over the past few years. In the reporting year, twelve events, two of which were felt, are thought to have been related to mining activity. Elsewhere in the country, seismic events were reported felt or heard like small earthquakes but, on analysis, proved to have been underwater explosions, quarry blasts or sonic booms. The latter included military jets and Concorde; six events were reported in total (Figure 9).

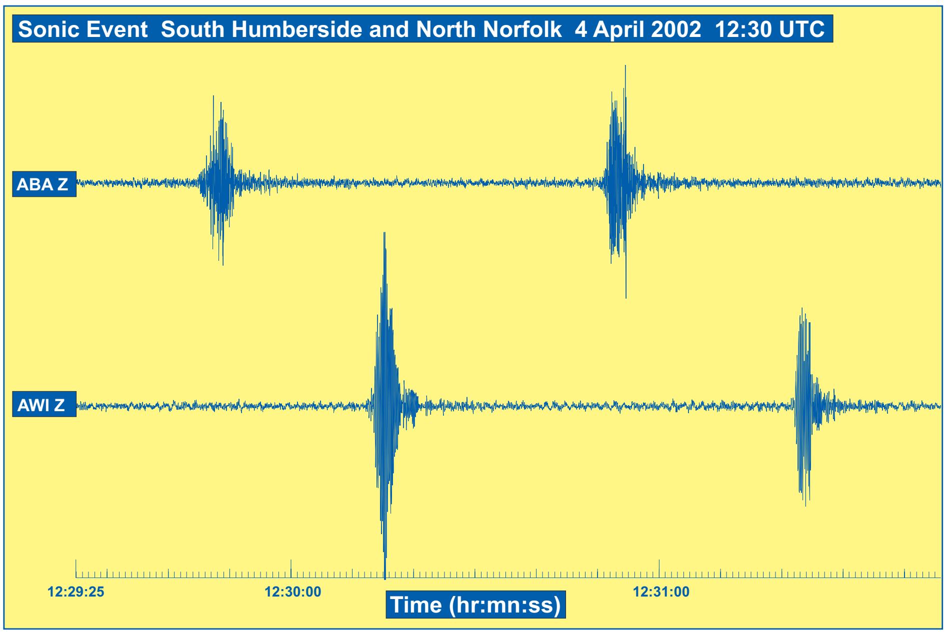

Figure 9. Seismograms recorded on two stations in the East Anglia network from the sonic event on 4 April 2002 12:30 UTC.

5.7 Global earthquakes

The monitoring network detects large earthquakes occurring elsewhere in the world depending on the event size and epicentral distance. Generally, those above magnitude ~5.8 are detected, however, for the largest distances the magnitude threshold is somewhat higher. In addition to automatically triggered detections, data is extracted from a number of networks based on location and origin time reported by the United States Geological Survey (USGS). During the period April 2002 to March 2003, a total of 263 teleseismic earthquakes were detected and analysed. The data are made available to international agencies and are used for various studies of global seismology. Of particular importance is that phase readings are integrated with the catalogues of global organisations such as the International Seismological Centre (ISC) and the European Mediterranean Seismological Centre (EMSC). The study of teleseismic earthquakes can provide valuable information on the structure beneath the UK, which helps to improve location capabilities for local earthquakes. Recent studies based on teleseismic earthquakes recorded in the UK include work on P-wave tomography (Arrowsmith et al., 2001) and receiver functions (Tomlinson, 2001) .

The Molise earthquake on 31 October 2002 (magnitude 5.5) struck the town of San Giuliano di Puglia in southern Italy and resulted in 29 deaths, including 27 children and teachers in the local school building. The destruction of the school (Figure 10), with lesser damage elsewhere in the village raised questions about building design and construction in an area previously thought to be one of low seismicity. The school had been extended, two years previously, with the addition of a second storey.

Figure 10. Aftermath of the magnitude 5.9 earthquake, Southern Italy on 31 October 2002. Photograph supplied courtesy of Dr. Romano Camassi, INGV.

A magnitude 7.9 Mw earthquake in Central Alaska on 3 November 2002 was the largest global earthquake in the reporting period (Figure 11). It caused extensive damage to many roads in the area and also to supports on the Trans-Alaska pipeline, on which operations were suspended. The total cost of the damage has been estimated at US$20 million. It was felt throughout the epicentral area, in northern British Columbia, western Alberta and Northwest Territories, and was also felt, by people in high-rise buildings, in Seattle, some 2,350 km away. The earthquake occurred on the Denali-Totschunda fault system, which is one of the longest strike-slip fault systems in the world.

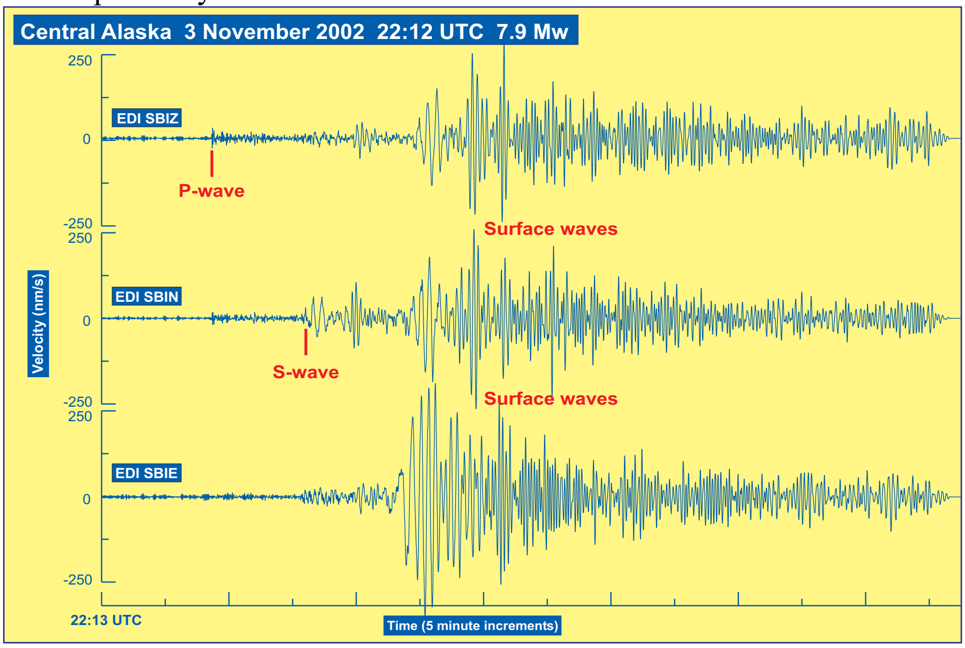

Figure 11. Seismogram of ground velocity recorded by the broadband seismometer in Edinburgh from the Central Alaska earthquake on 3 November 2003 22:12 UTC.

On 22 January, 29 people were killed, 300 injured, and about 10,000 made homeless by a magnitude 7.6 earthquake near Colima, Central Mexico. This is a seismically active zone near the junction of three tectonic plates: the North American Plate to the northeast, the Rivera Plate to the northwest, and the Cocos Plate to the south.

In addition to providing seismic recordings of global earthquakes to international data centres on a routine basis, BGS provides the Red Cross, DFID and UK rescue services, with rapid alerts and background information to assist in their response planning following destructive events.

6. Development of the Service

The network developed to March 2003, is shown in Figure 12 with its detection capability in Figure 13. An outline of its development is given below followed by the specific aims for the 2002/03 programme, and the results achieved in that reporting period.

6.1 The UK network

In the late 1960s, BGS installed an eight-station short period network of seismometers, with an aperture of 100 km, linked to Edinburgh by radio where data were recorded on a slow running, FM magnetic tape system (the Geostore). It recorded continuously for one week, at 16 Hz bandwidth, between tape changes. The system was largely a test-bed for portable, FM tape-recording equipment being developed for overseas missions in Turkey and elsewhere, and for crustal structure investigations of the UK such as LISPB (Bamford *et al.,* 1978). The availability of objective data, however, raised the profile of British earthquakes both within BGS and among Local Authorities, the media and the public. BGS became the focus for the

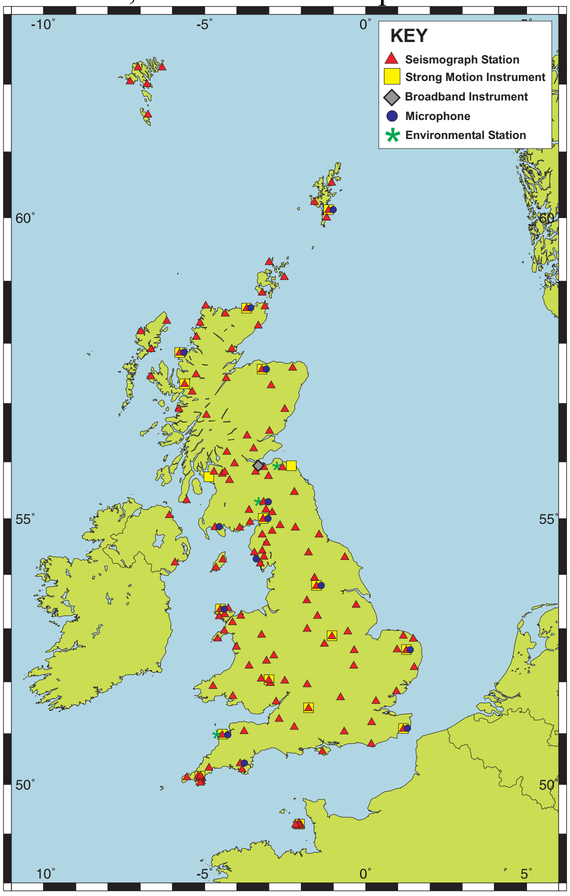

Figure 12. BGS seismograph stations March 2003.

provision of information and it embarked on a network expansion programme in the mid-1970s. Many earthquakes were being felt in southern England which were not detected in Scotland (threshold 3.5 ML). Mainly in response to mining-induced earthquakes in the Potteries, a major network expansion took place in the Midlands and South Wales, at that time, with the support of the Department of the Environment (DoE). At the end of that decade and in the early 1980s, the Department of Trade and Industry (DTI) sponsored studies of North Sea seismicity and, in Cornwall, in connection with the Hot Dry Rock geothermal project. Later, the nuclear industry supported relatively long-term monitoring operations around specific sites but in the context of the background network being developed.

Recognising the importance of cross-border data exchange in low seismicity Europe, over a six-year period eight and then ten of the Member States joined an EC project to further this aim. This so-called Transfrontier project firmly established mechanisms for rapidly exchanging data and, more importantly, built the trust which has continued to facilitate the process to the present day. As a consequence, the Irish Sea and the North Sea became monitored far more effectively.

The major step in securing nation-wide coverage and a formal monitoring and information service came in 1988 when the DoE led a "Customer Group" of interested organizations to co-fund the service in the long term. Donations of the DTI and nuclear industry equipment helped considerably and, in 1995, the oil industry filled remaining gaps in north and northwestern Scotland following their interest in exploring the NW Atlantic Margin. With support from HSE's Offshore Division and the Faroese Geological Survey, a further extension was made into the Faroe islands at the end of the decade.

Digital recording of data and automated, rapid transfer of the information to the BGS recording centre in Edinburgh was introduced in the late 1980s. To capture strong ground movements from small nearby earthquakes and from larger distant ones, the high sensitivity network was supplemented with strong motion accelerometers from 1990 and that development continues.

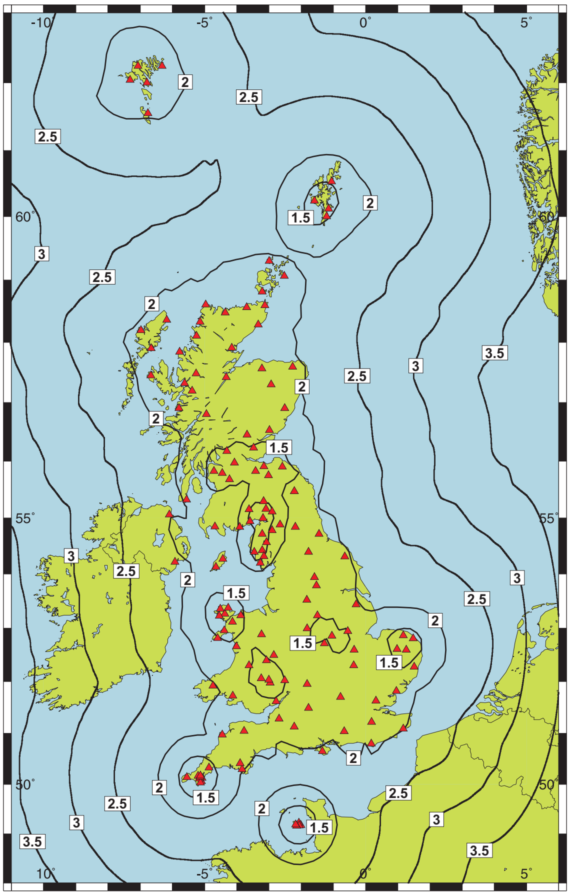

Figure 13. Detection capability of the network, March 2003. Contour values are Richter local magnitude (ML) for 20 nm of noise and S-wave amplitude twice that at the fifth nearest station.

The present monitoring network consists of 146 seismograph stations across the UK. Most of the stations have single, vertical component, short-period Willmore MK-III seismometers, although there are also a number of three-component Willmore MK-III seismometers and three-component, strong motion accelerometers. The primary aim of the network is to develop a national database of seismic activity in the UK for seismic hazard assessment and to provide a response to felt earthquakes. In addition, data are made available to the academic community both within the UK and overseas for investigations of crustal and upper mantle structure and processes. However, these objectives are presently restricted by the limited bandwidth and dynamic range of the seismic data acquisition systems. The current method of analogue telemetry limits the dynamic range of the data acquisition and, given the extremely wide dynamic range of natural seismic signals, this means that instrumentation capable of recording small local micro-earthquakes will not remain on scale for larger signals. Also, short period sensors cannot easily record long period signals from regional and teleseismic surface waves that can provide important information on crustal and upper mantle structure.

Over the past two years, BGS has begun to upgrade its three-component base stations to use 24-bit digital data acquisition. This equipment will give a higher dynamic range (increased to 140dB from the current 72dB) and will provide high quality on-scale data for larger earthquakes at closer epicentral distances. A total of five, three-component stations using 24-bit digital data acquisition have now been installed. These are at Bonnylands, Edinburgh, Eskdalemuir, Hartland and Paisley. The seismometer at Bonnylands is co-located with an existing strong motion accelerometer. Similar upgrade of the strong-motion data acquisition will mean that the two instruments will complement each other, with a wide degree of overlap, to ensure high quality recording of seismic data across a wide range of magnitudes for local, regional and teleseismic events. In addition, 24-bit data acquisition has been installed at the single vertical component station at Broad Law (EBL) within the LOWNET network around Edinburgh, as part of developments to deploy a full 24-bit seismic network using digital radio telemetry. New seismometers and 24-bit digitizers have been purchased to allow the upgrade of a single subnetwork that uses digital radio telemetry. This equipment was delivered in March 2003 and is currently being tested, with the intention of deployment in an area of high seismicity.

The QNX SEISLOG data acquisition equipment has now been installed at all sites across the UK network, except Borders, Cumbria, Devon and Torness. QNX gives a number of advantages over the VME system; increased processing power, larger memory capacity (from 8 Gbyte to upwards of 60 Gbyte), improved communication links using Ethernet cards and ISDN links (digital telephone lines), together with greater portability. Eleven of the QNX SEISLOG systems have 60 Gbyte storage capacities giving a hundred days of continuous data. These large capacity disks help to prevent losses of relevant data if the event-triggered systems miss spurious events, very small earthquakes and sonic booms which are reported and investigated some time after the event.

6.2 Strong motion

Obtaining records of strong ground motion for hazard assessments and engineering applications is difficult in areas of low to medium seismicity owing to the infrequency of larger earthquakes. In recognition of the importance of measured strong ground motions, the project has focused on developing a distribution of three-component instruments, which would remain on-scale for the larger British earthquakes when the high sensitivity network saturates. The present strong motion data acquisition is designed to give on-scale recording up to ground accelerations of 0.1g. Upgrade of the acquisition to use 24-bit recording will allow the upper limit to be increased to 0.25g, while at the same time providing considerable overlap with high sensitivity instrumentation located at the same sites.

6.3 Broadband

Broadband seismometers record ground motion over a wider frequency range than conventional short period instruments. These instruments are typically used for analysis of large earthquakes at teleseismic distances, which generate longer period waves than the typical small to moderate earthquakes in the UK. Broadband data is also very valuable for analysing large earthquakes in the UK. As well as containing information on the nature of the seismic source, and the deep Earth through which the waves have passed, teleseismic data recorded on broadband seismometers may also be used to improve understanding of crustal structure in the locality of the recording instrument. The analysis of surface waves from regional earthquakes can further help to improve the model of crustal structure. Improved crustal models will lead to greater accuracy in the determination of UK earthquake epicentres, focal mechanisms and the crucial (for hazard assessment) depths of occurrence. The BGS broadband station at Edinburgh continues to provide high dynamic range, 24-bit continuous data. Continuous, near real-time data from this station are available from the BGS web pages in the form of 24-hour helicorder records and also from the AutoDRM (Automatic Data Request Manager). Additional broadband data are readily available from the United States IRIS station hosted by BGS at Eskdalemuir Observatory. A temporary broadband station was installed at Rubha Reidh in northwest Scotland and this will be made permanent in the coming year. Planned broadband installations at the Hartland and Lerwick observatories have been delayed, but will also be completed in the coming year. High-speed Internet connections at these sites will allow the transfer of continuous data to Edinburgh.

6.4 Environmental monitoring

Environmental monitoring is becoming increasingly important in modern life. Many cities now have air pollution monitoring equipment but national background levels and wide area effects are often not so well studied due to the high cost of collecting data from a wide-spread network. The costs are especially acute where the data is required on-line, due to the extra expense of telemetry equipment. Using the existing infrastructure of the UK seismograph monitoring network, with its remote stations giving continuous on-line data stretching from the Faroe Islands in the north, to Jersey in the south, a cost-effective environmental monitoring network can be provided. Environmental data collected from sensors interfaced to this network would allow users to inspect the data in real-time or transfer it at intervals via modem or the Internet. In principle, any environmental sensor can be interfaced to the network.

Currently, there are four environmental stations in operation in the UK: one on the outskirts of Edinburgh, at Stoneypath; two in Eskdalemuir, at the geophysical observatory; and a station, monitoring meteorological parameters, at Hartland Observatory, Devon. Following concept development near Edinburgh, a more comprehensive system was installed at Eskdalemuir Observatory during 1999. Here, the sensors monitor a variety of pollution and meteorological parameters: concentrations of ozone, sulphur dioxide, and nitrogen oxides; and wind speed and direction, air temperature, soil temperature, rainfall, humidity, surface wetness, ultra-violet (UVB), nuclear radiation and sunshine. The Eskdalemuir data are recorded using a Campbell Scientific logger and a BGS-designed logger, both of which are interfaced to a networked computer. Eskdalemuir Observatory has the advantage of being a Meteorological Office site and so direct comparisons can be made between the standard Meteorological Office data and the BGS-recorded measurements. At Hartland Observatory, a Campbell Scientific logger records a range of meteorological parameters including temperature, humidity, wind speed and direction, rainfall and solar radiation. At Stoneypath measurements of temperature, humidity, UVB, air temperature, ground temperature, humidity and nuclear radiation are made. Data from all the environmental stations can be provided to users by e-mail, and software to enable data to be viewed and downloaded on-line using a Web-browser has been developed.

Further developments, including extended coverage of the UK's rural environment, awaits support from potential customers in the environmental, utilities and resource sectors (public and private) which could benefit from such a nationwide facility; for example, in monitoring both short term events and predicting impacts of longer-term climate change and pollutant fluxes.

6.5 Specific aims of the 2002/2003 programme

The development objectives for the year, set in May 2002 were:

(i) Continue the upgrade of the remaining VME Seislog data acquisition systems to QNX Seislog.

(ii) Deployment of previously purchased broadband sensors at up to four stations with 24-bit data acquisition and high speed internet connections to Edinburgh.

(iii) Upgrade of three-component stations by installation of 24-bit digitizers to provide high dynamic range digital data. The number of sites will be determined by funding constraints and opportunities.

(iv) Capture of more strong motion data in collaboration with the nuclear industry.

(v) Collaboration with Universities.

(vi) Maintain a watching brief on archives held by other organisations with a view to seeking the transfer to Edinburgh of any considered at risk.

(vii) Continue collaboration with the IASPEI international effort to make archives available electronically.

Networks in Galloway, Moray and North Wales have been upgraded to use QNX SEISLOG data acquisition (i) leaving only Borders, Cumbria, Devon and Torness to be completed. A temporary broadband station was installed at Rubha Reidh in northwest Scotland and this will be made permanent this year. Planned broadband installations at Hartland and Lerwick (ii) have been delayed, but will be completed this year. A high dynamic range, three-component station (iii) was installed at Bonnylands (HBL2) as part of the Hereford network. During the year, a further nine records from six strong motion stations (iv) have been obtained from the earthquakes in Dudley and Annan (Table 1). Collaboration with the Universities of Bristol, Leicester, Leeds and Cambridge has continued and new initiatives have started with Durham and Imperial College, London (v). Contact with archives outside BGS has been maintained (vi) with the addition of Soil Mechanics UK Historical Data and British Association for the Advancement of Science Seismological Committee archives. Data have been supplied to IASPEI and work is progressing with the international effort to make archives available electronically (vii).

7. Uses of the Seismic Data

In addition to the specific needs of the Customer Group members, the instrumental seismic database is used by a variety of organisations both in the UK and worldwide. A summary of the use made of this 33-year catalogue and digital archive of earthquakes, during the past year, follows:

7.1 Seismic Hazard studies

Understanding of seismic hazard in the UK has evolved considerably since one of the first ever studies was conducted by Lilwall (1976). He started with the assumption that seismicity was uniformly distributed throughout the country, to arrive at an "average" hazard value of 0.2 g with annual probability of 10^{-4}. This result was duplicated by Irving (1982). During the 1980s, much work was done on improving knowledge of British earthquakes, culminating in the publication of the first unified parametric catalogue (historical and modern data) for the UK in 1994. This data set was used for the production of a series of seismic hazard maps in 1996, compiled by BGS and AEA Technology, for DTI. They showed that "average" hazard for the UK (in terms of a median value) is actually around 0.15 g at the 10^{-4} per year probability level. An up-dated version of this map (2002), reproduced here as Figure 14, has been determined using both the distribution of earthquakes and more interpretation of the underlying tectonic structure.

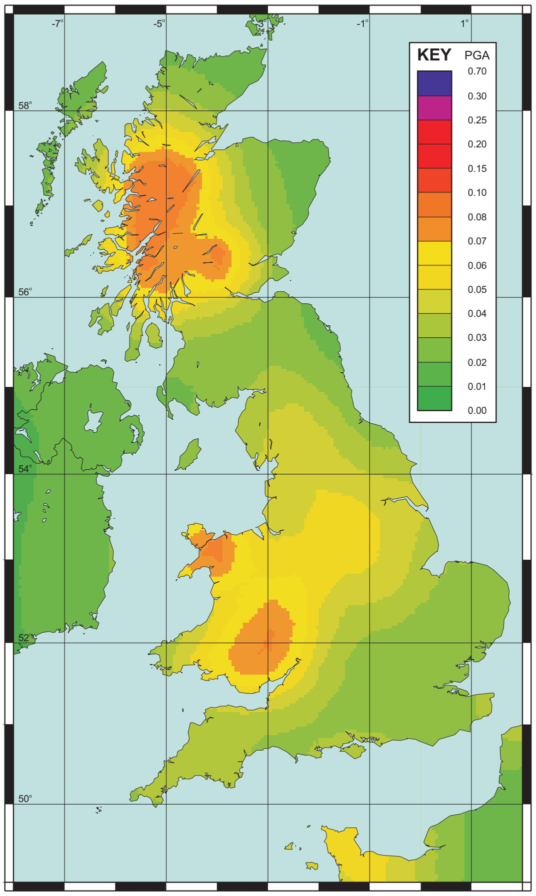

Figure 14. Current draft UK seismic hazard map.
Horizontal PGA with return period of 475 years.

In Figure 14, the 475 year return period is the yardstick used by engineers for ordinary structures. It shows that if you are standing in the yellow contour area in the country indicating a level of 0.05g there would be a 10% chance of experiencing an acceleration of 0.05g or greater in 50 years. The highest value of shading is around 0.09g. The highest hazard, generally, is away from major urban areas.

The seismic source model used in 1996 was revised slightly for use in the Global Seismic Hazard Assessment Programme (GSHAP) for the world hazard map published in 1999, and this version was also used in the European hazard map that resulted from the SESAME project in 2002. The model continues to be refined with new data and ideas; most recently in collaboration with the Geological Survey of South Africa, which has similar problems in producing a quantifiable hazard assessment in a low seismicity region.

Individual recent earthquakes may prompt local reconsiderations of parts of the model. For example, the Arran earthquake of 1999 has implications for the southern limit of the Hebridean source zone. However, more important is the cumulative effect of prolonged instrumental monitoring, especially where it is possible to build up a substantial database of fault plane solutions that can permit the discrimination of areas of different styles of seismogenic fault activity.

7.2 Attenuation Studies

Data recorded on BGS strong motion accelerometers has shown that the existing attenuation laws currently used for the UK (PML, 1988; Ambraseys and Bommer, 1995; Dahle et al. 1990) significantly overestimate attenuation when compared to recorded ground accelerations for moderate sized earthquakes in the UK. To-date, 41 three-component acceleration records (Table 1) have been recorded for earthquakes with magnitudes between 1.1 and 4.7 ML at distances of between 3 and 285 km. Nine of these records were recorded in the reporting year. These, and other on-scale recordings, can be used to derive a spectral attenuation model by inversion of Lg-wave observations throughout the UK, and, given accurate source parameters, stochastic methods can be used to simulate ground motion (Boore, 1983) and provide more realistic empirical attenuation relationships. The better understanding of attenuation in the UK is one of the most critical requirements for improving the accuracy and value of the quantified seismic hazard assessment used by industries and their regulators.

7.3 UK Crustal Structure

P- and S-wave travel times for local seismic events recorded on the BGS seismograph network can be used to jointly invert for earthquake hypocentres and crustal velocities (Kissling *et al*., 1994). 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 carried out by various institutes. These models are an important starting point and are used to constrain the initial velocity model for the inversion. The development of more appropriate regional velocity models will help better identify the true spatial distribution of seismicity and the relationship with geological features such as faults. In addition, these minimum 1-D models can be used as a starting point for three-dimensional local earthquake tomography (Thurber, 1993). Joint inversion of teleseismic receiver functions and surface wave dispersion can also be used to model crustal and upper-mantle structure (Julia *et al.,* 2000).

7.4 Data exchange

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 readings for regional events are distributed to the European-Mediterranean Seismological Centre to assist with relocation of regional earthquakes and rapid determination of destructive earthquakes. Broadband waveform data are made available to ORFEUS, the regional data centre for seismic waveforms. Phase data are made available to the International Seismological Centre, an agency providing definitive information on earthquake hypocentres. Data has also been contributed to a programme for calibrating the international network of stations for monitoring the Comprehensive Test Ban Treaty (CTBT). Earthquakes and explosions with magnitudes ≥2.5 ML, within 1000 km of the UK are relevant, and data from such events have been processed and submitted to the International Data Centre in Vienna.

7.5 Focal mechanisms

Earthquake focal mechanisms provide information on specific fault types and tectonic processes occurring within the crust and can be used to better understand the relationship between earthquakes and local geology. In collaboration with the Nuclear Installations Inspectorate (NII), a systematic program of revising the focal mechanism catalogue is continuing. As more focal mechanisms are obtained, we gain a better understanding of the stresses and tectonic processes that cause earthquakes in the UK. The results are being compiled in a GIS database showing the 47 fault plane solutions and stress axes orientations. Overall, a variety of focal mechanisms are observed and the relationship between tectonics and local geology appears complex. There is no clearly defined relationship between source mechanism and either locality or depth. However, an estimate of the regional stress field can be made using an inversion method to look for the best-fitting stress tensor that lies in the overlap between the families of stresses associated with a population of focal mechanisms for earthquakes in this database. This gives an estimate of both the orientations and relative magnitudes of the principal stress directions. The principal compression is found to be in a northwest southeast direction and is consistent with compression due to first order plate motions.

7.6 Earthquake statistics

The UK instrumental database covers the past 33 years, although in the early years, to 1978, it is probably only complete for magnitudes of 3.5 ML and greater. Since 1979, the completeness threshold is magnitude 2.5. The total statistics for earthquakes of magnitudes ≥ 2.0, shown in Figure 15, illustrates the recent history of UK seismicity. Some apparent cycles of activity are evident but no significance can be placed on them at this stage. Figure 16 shows the record of earthquakes reported to have been felt, separating out those in coalfield areas where the majority will have been caused by mining. The variable reporting of the latter set, often prevents any meaningful analysis. However, the increase in 1996 can be attributed to the Monktonhall series near Edinburgh and the miners strikes between 1983 and 1985 explain the low level at that time. The diminution of deep mining activity in recent years has been accompanied by a significant reduction in seismicity from coalfield areas. Peaks in the distribution of natural earthquakes can be attributed to swarm activity in 1974 (Kintail), 1980 (Carlisle), 1981 and 1986 (Constantine), 1984 (North Wales) and in 2002 (Greater Manchester).

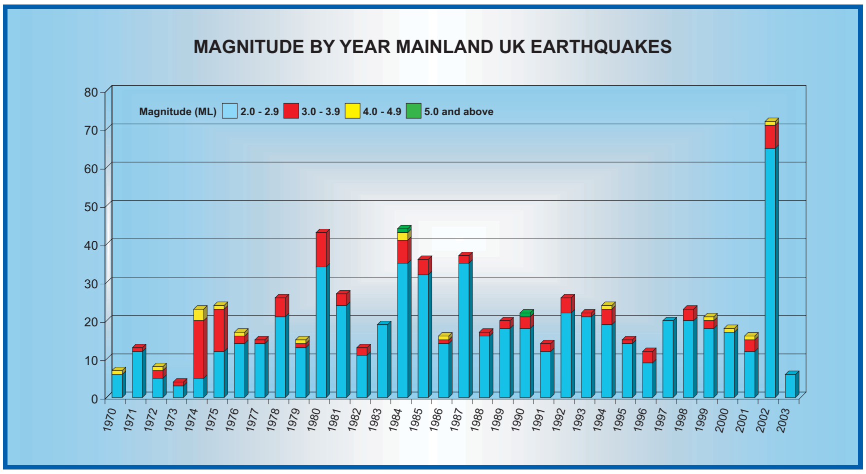

Figure 15. Histogram showing the number of events of magnitude 2.0 ML or greater, detected between 1970 to March 2003.

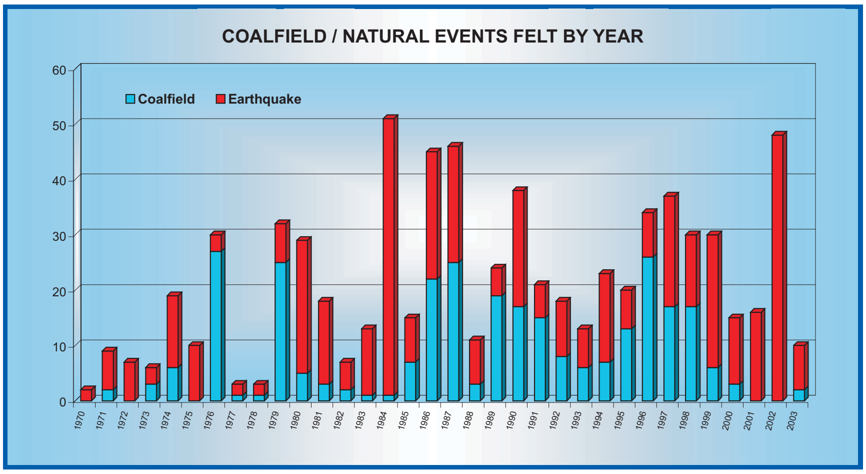

Figure 16. Histogram showing number of felt events 1970 – March 2003

7.7 Parliamentary questions and advice to Public Authorities, Industry and media

There were no parliamentary questions raised on seismicity issues during the year. Some 1171 enquiries were answered, with intense interest following the Dudley and Manchester earthquakes. Some 395 were from the media, including 87 for TV broadcasts and 126 for radio (Figure 17), following significant earthquakes. The broadcasting enquiries led to 46 TV and 110 radio interviews being conducted, most of them (42 and 107) prompted by UK earthquakes.

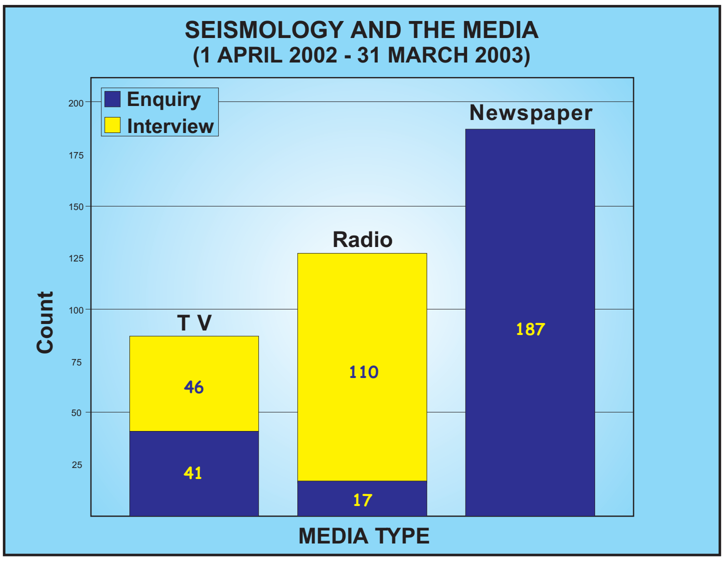

Figure 17. Histogram showing the number of media enquiries answered for UK and world earthquakes between 1 April 2002 and 31 March 2003.

7.8 Public Understanding of Science

A number of lectures and presentations were given to school and university students and other interested parties. The Internet home page has been a source of information for the public, media and other organisations, with over 3 million hits in the year including 526,846 in the week following the Dudley earthquake in September 2002 and 1,344,325 during and following the Manchester series. BGS, produced another updated earthquake information booklet to include the Dudley and Manchester earthquakes and a section on man-made events. This was distributed to the Customer Group in June 2003 and is being used in school educational packs, at workshops for schools, at various science festival events throughout the country and for general enquiries. Over 3000 copies of the booklet issued in April 2002 were distributed throughout the year. The BGS Open day (Figure 18) in Edinburgh in September attracted some 850 visitors with many of them visiting the earthquake display.

Figure 18. BGS Openday, September 2002. Photograph supplied by BGS.

7.9 The National Seismological Archive (NSA)

In the last year, two data collections have been added to the archive. The complete list of data held in the archives can be found in Annex E. The new additions are:

The Soil Mechanics UK Historical Data Archive
In 1981-2, Soil Mechanics Ltd was one of four organisations involved in extensive research into the history of British earthquakes, the other three being Principia Mechanica Ltd, British Geological Survey, and Imperial College London. The SML project led to the publication of a four-volume study of the history of British earthquakes, based around revaluation of 72 representative events. The material accumulated by this study has now been deposited with the NSA. It consists of three large boxes of materials, with folders for each of the earthquakes that were investigated, containing photocopies of source materials, working notes, etc. The intention is to preserve all this material in its present organisation, rather than attempting to merge it with similar data collected by BGS.

British Association for the Advancement of Science Seismological Committee Archive
The Seismological Committee of the BAAS was founded in 1841, and continued intermittently up until the 1980s. The surviving material relating to this committee was in the hands of Dr John Hudson, Cambridge University, who has now deposited the material with the NSA. It consists principally of copies of the annual reports of the committee (some printed, others in original typescript), together with material relating to the Gray-Milne

Seismological Trust, a charitable fund established by Thomas Gray in his will, and extended by his friend. John Milne (d. 1913). This fund was created to support research into the physics of the earth. The administration of the fund has now been passed from the defunct BAAS Committee to the British Geophysical Association, which is a joint association of the Geological Society and the Royal Astronomical Society.

7.10 External Collaboration

Throughout the period of the project, there has been a number of establishments which have utilised the BGS data to achieve a greater understanding of the Earth's structure and earthquake processes. Often, these research results feed back into the information service through improvements in earthquake parameter determinations and hazard assessments. More details about the projects can be found in Annex F. A summary follows:

- **Bristol University, mapping seismic discontinuities**: Sub-crustal reflecting structures have been found under the Orkneys and the northern coast of Scotland.

- **Brunel University**, **Glaciotec project:** The possible influence of former ice sheets on crustal deformation and seismicity in Scotland since the last ice age (10,000 years ago) is being investigated, including the integration of seismicity, focal mechanisms, stress and crustal movement data.

- **Leicester University, UK velocity model:** Velocity models have been determined using teleseismic receiver functions from data recorded at three-component seismograph stations. These can be combined with gravity information to model pressure differences at depth in relation to present-day seismicity.

- **Leeds University:** Data recorded on a temporary deployment of broadband sensors at BGS seismograph stations has been used to investigate the nature of the Earth's core-mantle boundary; results contribute to the understanding of plate tectonics.

- **Cambridge University**, **Atlantic Margins Project:** The Atlantic Margins Project, to investigate deep structure off the NW coast of Scotland, has used low frequency seismic sources with recording both at sea and on the BGS seismic network, to provide new crustal structure results for the region.

- **Imperial College/ARUP:** Together with BGS, recently acquired UK strong motion and unsaturated short-period data is being analysed with a view to establishing more realistic seismic attenuation laws for the country, which will impact strongly on future hazard assessments and the confidence placed in them.

- **Durham University, Earthquakes and Cenozoic Uplift**: Modelling suggests that UK earthquakes result from ongoing Cenozoic uplift tectonics associated with anomalous upper mantle, and crustal weakening.

- **European and worldwide agencies**: BGS collaborates in project work, from time-to-time, and routinely provides data recorded on the UK network to European and global data integration centres (EMSC, ORFEUS, ISC and USGS) from where it is made openly available to researchers, engineers and hazard assessment specialists.

8. Dissemination of results

8.1 Near-immediate response

Customer Group members have received seismic alerts by e-mail whenever an event has been reported to be felt or heard by more than two individuals. In the case of sequences of events in coalfield areas, only the more significant ones are reported in this way. Some 37 alerts were issued to the Customer Group during the year.

Throughout the year, a monthly updated catalogue listing recent earthquakes and seismic alerts, giving details of UK and global earthquakes, has been available through an Internet home page (address: http://www.earthquakes.bgs.ac.uk). Questionnaires and updated information on the Dudley and Manchester earthquakes were also made available on the home page. Feedback suggests that the Seismology web site is being used extensively for the wide variety of seismological information it offers. In the past year, some 435,000 visitors (3 million hits) have been logged, an increase of over 45% on the previous year.

Remote telephone access to all the UK seismic stations is available and six of the principal BGS seismologists can obtain data directly from their homes. Two members of staff are on-call 24 hours-a-day to improve the response to earthquakes and seismic alerts outside working hours. These advances have resulted in considerable improvements in the immediate response capability for UK and global events including enquiries which prove to be spurious or of non-earthquake origin. Most of the UK is now covered for earthquakes with magnitudes of 2.0 ML or greater.

8.2 Medium-term response

Preliminary bulletins of seismic information have continued to be produced and distributed on a routine basis to the Customer Group within six weeks of the end of a one month reporting period.

8.3 Longer-term

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 2002, it was issued within four months.

9. Programme for 2003/04

During the year, the project team (Annex C) will continue to detect, locate and seek to understand, natural seismicity and man-made events in and around the UK. The information will be supplied to the Customer Group with minimal delay. The database and archive of UK seismicity and related material will be maintained and extended, with information on holdings disseminated on the Internet. Modest improvements will be made to network capabilities. The following list gives specific details on advances anticipated for 2003/04, subject to the continuation of funding at least at the current level and without any unexpected closures of site-specific networks.

(i) Upgrade two of the remaining VME Seislog data acquisition systems to QNX Seislog.

(ii) Deploy broadband sensors at up to four sites with 24-bit data acquisition and high-speed Internet connection to Edinburgh.

(iii) Upgrade one subnetwork to 24-bit data acquisition and digital telemetry, and install a broadband sensor at the central recording site.

(iv) Continue development on data acquisition, network automation and analysis software.

(v) Update the home page

(vi) Continue research collaboration with Universities.

(vii) Review significant earthquakes in the UK over the past 25 years, with special focus on source depth, source mechanism and spectral source parameters.

(viii) Derive spectral attenuation model from seismic wave observations throughout the UK.

(ix) Finalize work on the Manchester earthquake sequence.

(x) Finalize work on stress tensor inversion using focal mechanisms for UK earthquakes.

(xi) Maintain a watching brief on archives held by other organisations with a view to seeking the transfer to Edinburgh of any considered at risk

10. Acknowledgements

We particularly wish to thank the Customer Group (listed in Annex A) for their participation, financial support and input of data and equipment to the project. Station operators and landowners throughout the UK have made an important contribution and the technical and scientific staff in BGS (listed in Annex C) 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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Table 1
Measured Ground Accelerations Recorded on Strong Motion Instruments in the UK
1994 - March 2003

Date	ML	Depth	Event Location		Locality	Distance	Z	NS	EW	Station	Station Grid Ref	
YearMnDD		km	KmE	KmN		km	mm/s^2	mm/s^2	mm/s^2	Code	KmE	KmN
19940317	3.1	21.7	302.3	294.2	NEWTOWN	61	4.3	4.2	3.6	HBL2	328.8	239.7
19940611	2.2	7.4	172.7	27.9	CONSTANTINE	7	8.0	8.7	14.4	CRQ	173.5	34.6
19940817	3.1	3.0	174.5	816.7	ISLE OF SKYE	18	4.3	3.9	2.8	KPL	180.2	833.5
19961110	3.8	8.3	143.7	17.2	PENZANCE	34	62.0	52.7	26.9	CRQ	173.5	34.6
19980403	1.1	6.7	325.3	569.4	ANNAN	3	3.7	9.6	6.3	BCC	322.0	569.7
19980528	1.5	12.0	328.8	553.7	WIGTON	17	0.9	2.4	1.3	BCC	322.0	569.7
19980721	2.0	12.8	295.8	579.9	LOCHARBRIGGS	28	1.1	0.4	0.4	BCC	322.0	569.7
19990121	2.8	16.9	538.7	357.1	BOSTON	95	8.3	10.1	6.3	AEU	618.9	307.5
19990304	4.0	19.0	194.8	616.2	ARRAN	136	1.4	4	3.6	BCC	322.0	569.7
19990314	1.9	11.0	295.9	579.2	DUMFRIES	28	0.7	0.2	0.3	BCC	322.0	569.7
19990617	2.8	21.1	360.9	233	HEREFORD	33	8.1	20	12.1	HBL2	328.8	239.7
19990713	1.8	10.2	376.9	-76.1	JERSEY	20	3.7	5.7	6.8	JDG	396.6	-78.4
19990903	2.1	4.2	311.4	593.4	JOHNSTONEBRIDGE	26	1.1	0.5	0.8	BCC	322.0	569.7
19991025	3.6	14.1	292.2	230.8	SENNYBRIDGE	38	10.8	37.8	19.8	HBL2	328.8	239.7
20000107	1.8	10.3	295.8	579	DUMFRIES	28	0.5	0.2	0.3	BCC	322.0	569.7
20000212	2.7	8.8	193.1	673.5	LOCHGILPHEAD	166	0.2	0.2	0.2	BCC	322.0	569.7
20000424	2.6	13.8	347.6	541.5	CALTHWAITE	38	1.3	7.1	1.4	BCC	322.0	569.7
20000622	2.6	23.9	239.5	343.5	LLEYN PENINSULA	47	1.7	2.1	3.2	WCB	230.6	389.9
20000808	2.7	24.4	439.6	529.9	MIDDLESBROUGH	124	0.3	0.2	0.3	BCC	322.0	569.7
20000923	4.2	13.1	426.5	265	WARWICK	76	17.2	16.6	20.8	KEY2	462.1	331.7
20000923	4.2	13.1	426.5	265	WARWICK	87	7.1	5.5	6.6	SWN	413.9	179.4
20000923	4.2	13.1	426.5	265	WARWICK	101	5.0	6.7	5.9	HBL2	328.8	239.7
20010513	3.0	11.5	295.5	579.6	DUMFRIES	28	5.3	4.7	2.8	BCC	322.0	569.7

Table 1
Measured Ground Accelerations Recorded on Strong Motion Instruments in the UK
1994 - March 2003

Date	ML	Depth	Event Location		Locality	Distance	Z	NS	EW	Station	Station Grid Ref	
YearMnDD		km	KmE	KmN		km	mm/s^2	mm/s^2	mm/s^2	Code	KmE	KmN
20010531	3.6	26.4	215.6	127.2	OFF HARTLAND POINT	98	8.0	7.5	7	CRQ	173.5	34.6
20010627	2.2	7.2	382.1	485.8	SEDBERGH	103	0.2	0.1	0.2	BCC	322.0	569.7
20011010	3.1	6.5	313.3	200.7	BARGOED	42	5.0	15.2	16	HBL2	328.8	239.7
20011028	4.1	11.6	477.1	328.3	MELTON MOWBRAY	15	121.0	190	212	KEY2	462.1	331.7
20011028	4.1	11.6	477.1	328.3	MELTON MOWBRAY	144	6.9	10.6	14.2	AEU	618.9	307.5
20020922	4.7	14.0	389.3	292.8	DUDLEY	80	22.0	17	21	HBL2	328.8	239.7
20020922	4.7	14.0	389.3	292.8	DUDLEY	82	153.0	84	142	KEY2	462.1	331.7
20020922	4.7	14.0	389.3	292.8	DUDLEY	285	0.7	0.6	10	BCC	322.0	569.7
20020922	4.7	14.0	389.3	292.8	DUDLEY	116	10.0	12	19	SWN	413.9	179.4
20020922	4.7	14.0	389.3	292.8	DUDLEY	230	10.0	14	15	AEU	618.9	307.5
20020922	4.7	14.0	389.3	292.8	DUDLEY	147	11.0	18	16	LDU	429.0	435
20021021	3.9	2.8	387	398	MANCHESTER	100	2.0	6	4	KEY2	462.1	331.7
20021021	3.5	5.0	385.5	397.1	MANCHESTER	101	2.2	6.2	4.1	KEY2	462.1	331.7
20021029	1.8	16.6	313	573.7	ANNAN	10	0.5	0.7	0.8	BCC	322.0	569.7

CONTRIBUTORS TO THE PROJECT 2002 / 2003

OFFICE OF THE DEPUTY PRIME MINISTER

BNFL Magnox Generation

SCOTTISH WATER

ALCAN

HSE Health & Safety Executive

Western Frontiers Association

British Energy

NATURAL ENVIRONMENT RESEARCH COUNCIL

BNFL

UKAEA Restoring our Environment

ScottishPower generation uk

East Renfrewshire COUNCIL

Scottish and Southern Energy plc

EARTHQUAKES WITH MAGNITUDE 2.0 AND ABOVE, RECORDED IN THE UK AND OFFSHORE WATERS: 2002

Date			Time			Lat	Long	Grid Ref.		Depth	Mag	Locality	Int
Year	Mo	Dy	Hr	Mn	Secs	km N		km E	km N	(km)			EMS
2002	1	28	0	30	14.8	51.70	-3.26	313.1	200.9	6.3	2.5	BARGOED-MID GLAMORGAN	
2002	1	30	17	6	9.8	53.31	1.23	614.9	383.9	21.9	3.5	SOUTHERN NORTH SEA	
2002	2	12	19	13	16.2	51.70	-3.26	313.2	201.0	5.2	3.0	BARGOED-MID GLAMORGAN	4+
2002	2	14	19	0	38.2	59.79	2.54	654.4	1109.5	15.0	4.0	NORTHERN NORTH SEA	
2002	2	17	15	44	6.7	51.71	-3.26	312.9	201.6	2.4	2.0	BARGOED-MID GLAMORGAN	
2002	3	16	0	21	24.7	57.01	-4.72	234.9	793.9	7.7	2.0	INVERGARRY-HIGHLAND	
2002	4	23	21	30	26.7	53.50	2.50	698.2	409.4	10.0	2.7	SOUTHERN NORTH SEA	
2002	4	26	3	25	31.3	52.83	-4.39	239.4	328.8	11.9	2.1	PWLLHELI-GWYNEDD	
2002	5	2	1	48	3.1	57.02	-4.80	230.3	795.0	3.3	2.3	LOCH LOCHY-HIGHLAND	3+
2002	5	3	18	44	58.9	57.33	-5.33	199.3	831.2	3.5	2.3	SHIEL BRIDGE-HIGHLAND	3+
2002	5	3	18	46	29.7	57.32	-5.33	199.5	830.8	2.7	2.0	SHIEL BRIDGE-HIGHLAND	3+
2002	5	24	1	49	41.0	61.74	3.10	669.3	1328.1	15.0	2.4	NORWEGIAN COAST	
2002	5	25	21	4	1.0	57.40	-5.78	173.0	840.4	11.7	2.1	PLOCKTON-HIGHLAND	
2002	6	20	17	26	41.8	51.57	-3.08	325.1	186.0	14.3	2.9	CARDIFF-S GLAMORGAN	3+
2002	7	20	2	10	34.2	52.90	2.22	683.6	341.7	15.0	2.3	SOUTHERN NORTH SEA	
2002	8	25	4	43	31.6	58.11	0.73	560.7	916.7	20.0	3.3	CENTRAL NORTH SEA	
2002	8	28	10	9	54.9	61.62	-0.20	495.5	1305.9	15.0	2.3	NORTH OF SHETLAND	
2002	9	4	10	48	5.7	56.60	-5.75	169.9	751.2	7.6	2.3	LOCHALINE-HIGHLAND	
2002	9	6	12	30	45.9	61.50	3.41	687.8	1303.1	5.6	3.1	NORTHERN NORTH SEA	
2002	9	14	4	40	42.9	59.04	1.65	609.2	1023.1	15.0	3.4	NORTHERN NORTH SEA	
2002	9	18	5	20	10.3	51.71	-3.59	290.3	202.9	1.5	2.1	GLYN-NEATH-W GLAMORGAN	
2002	9	22	23	53	14.8	52.53	-2.16	389.3	292.8	14.0	4.7	DUDLEY-W MIDLANDS	5
2002	9	23	3	32	15.9	52.52	-2.14	390.8	291.7	9.3	2.7	DUDLEY-W MIDLANDS	3+
2002	9	30	6	44	51.2	48.08	-3.23	308.3	-201.2	21.7	4.5	NORTH-WEST FRANCE	4+
2002	10	1	23	30	27.6	59.63	2.10	631.1	1089.6	19.5	2.0	NORTHERN NORTH SEA	
2002	10	7	22	31	47.8	50.53	-3.74	276.7	71.2	4.5	2.1	ASHBURTON-DEVON	
2002	10	12	0	42	26.1	59.93	0.02	512.7	1118.2	12.3	3.5	NORTHERN NORTH SEA	
2002	10	14	13	12	21.5	48.40	-6.99	30.6	-155.1	15.0	3.1	ENGLISH CHANNEL	
2002	10	21	7	45	15.8	53.48	-2.20	387.0	397.6	5.0	3.2	GREATER MANCHESTER	4+
2002	10	21	8	4	58.7	53.50	-2.21	386.1	400.1	5.0	2.3	GREATER MANCHESTER	3+
2002	10	21	11	42	34.7	53.48	-2.20	387.1	398.3	2.3	3.9	GREATER MANCHESTER	5+
2002	10	21	11	42	56.9	53.48	-2.22	385.5	397.9	5.0	3.5	GREATER MANCHESTER	4+
2002	10	21	11	56	46.0	53.44	-2.14	390.8	393.8	5.0	2.0	GREATER MANCHESTER	
2002	10	21	16	22	21.8	53.48	-2.19	387.2	398.2	5.0	2.0	GREATER MANCHESTER	
2002	10	21	17	2	42.1	53.50	-2.21	386.0	400.6	5.0	2.2	GREATER MANCHESTER	
2002	10	21	22	34	38.3	53.47	-2.18	387.9	397.3	5.0	2.1	GREATER MANCHESTER	
2002	10	22	3	39	37.6	53.46	-2.22	385.5	396.3	5.0	2.9	GREATER MANCHESTER	4+
2002	10	22	3	54	2.4	53.46	-2.15	389.8	396.3	5.0	2.0	GREATER MANCHESTER	2+
2002	10	22	6	20	57.5	53.48	-2.20	386.6	398.6	5.0	2.0	GREATER MANCHESTER	
2002	10	22	12	28	8.4	53.47	-2.15	390.3	397.4	4.2	3.1	GREATER MANCHESTER	4+
2002	10	22	16	53	41.0	53.49	-2.15	390.4	399.1	5.0	2.4	GREATER MANCHESTER	2+
2002	10	23	1	53	28.8	53.48	-2.16	389.6	397.9	5.0	2.8	GREATER MANCHESTER	3+
2002	10	23	6	27	52.6	53.50	-2.14	390.9	400.2	5.0	2.0	GREATER MANCHESTER	
2002	10	23	19	18	11.6	53.49	-2.16	389.2	399.1	5.0	2.0	GREATER MANCHESTER	
2002	10	23	20	16	31.7	53.48	-2.16	389.2	397.8	5.0	2.2	GREATER MANCHESTER	3+
2002	10	23	20	31	28.8	53.48	-2.17	388.6	398.6	5.0	2.5	GREATER MANCHESTER	3+
2002	10	24	4	36	59.1	53.47	-2.16	389.3	397.1	5.0	2.3	GREATER MANCHESTER	
2002	10	24	4	38	36.9	53.48	-2.15	390.2	398.0	5.0	2.0	GREATER MANCHESTER	2+
2002	10	24	5	53	54.5	53.48	-2.20	386.8	398.4	5.0	2.2	GREATER MANCHESTER	
2002	10	24	7	52	54.4	53.48	-2.17	388.5	398.2	5.0	2.6	GREATER MANCHESTER	3+
2002	10	24	8	21	44.7	53.49	-2.18	388.1	399.3	5.0	2.0	GREATER MANCHESTER	
2002	10	24	8	24	54.7	53.49	-2.18	388.1	398.7	3.7	3.1	GREATER MANCHESTER	4+

EARTHQUAKES WITH MAGNITUDE 2.0 AND ABOVE, RECORDED IN THE UK AND OFFSHORE WATERS: 2002 (CONTINUED)

Date			Time			Lat	Long	Grid Ref.		Depth	Mag	Locality	Int
Year	Mo	Dy	Hr	Mn	Secs	km N		km E	km N	(km)			EMS
2002	10	24	14	56	40.7	53.50	-2.19	387.2	400.0	5.0	2.1	GREATER MANCHESTER	
2002	10	24	15	46	44.2	53.48	-2.20	387.0	398.4	5.0	2.8	GREATER MANCHESTER	3+
2002	10	24	16	34	38.8	53.49	-2.19	387.5	399.6	5.0	2.2	GREATER MANCHESTER	
2002	10	24	18	37	12.6	53.49	-2.21	385.9	399.0	5.0	2.6	GREATER MANCHESTER	3+
2002	10	24	19	0	45.8	53.49	-2.20	386.6	399.2	5.0	2.2	GREATER MANCHESTER	3+
2002	10	24	23	7	51.6	53.50	-2.21	386.1	399.9	5.0	2.2	GREATER MANCHESTER	
2002	10	25	0	19	27.1	53.49	-2.23	384.6	399.7	3.0	2.6	GREATER MANCHESTER	3+
2002	10	25	0	20	39.5	53.49	-2.21	386.3	399.5	2.0	2.6	GREATER MANCHESTER	3+
2002	10	25	0	25	44.5	53.50	-2.22	385.3	399.8	2.2	2.3	GREATER MANCHESTER	2+
2002	10	25	17	24	48.0	53.48	-2.19	387.2	398.6	3.3	2.6	GREATER MANCHESTER	3+
2002	10	27	7	26	50.0	53.49	-2.21	386.4	399.7	2.0	2.0	GREATER MANCHESTER	
2002	10	28	3	8	14.1	53.49	-2.19	387.4	399.7	5.0	2.0	GREATER MANCHESTER	
2002	10	28	19	25	59.1	53.48	-2.20	386.7	398.6	5.0	2.3	GREATER MANCHESTER	3+
2002	10	29	0	7	53.7	53.49	-2.20	386.9	398.8	5.0	2.2	GREATER MANCHESTER	3+
2002	10	29	4	42	52.0	53.48	-2.20	386.9	398.3	5.0	2.6	GREATER MANCHESTER	3+
2002	10	29	17	32	15.9	53.49	-2.21	386.1	399.0	5.0	2.4	GREATER MANCHESTER	3+
2002	10	31	1	50	57.4	53.48	-2.21	386.0	398.6	5.7	2.3	GREATER MANCHESTER	2+
2002	11	4	7	29	12.8	53.48	-2.17	388.8	398.3	5.0	2.3	GREATER MANCHESTER	2+
2002	11	4	7	32	32.0	53.47	-2.16	389.5	397.6	5.0	2.7	GREATER MANCHESTER	3+
2002	11	9	1	11	20.1	53.47	-2.17	388.9	397.5	5.0	2.1	GREATER MANCHESTER	
2002	11	9	1	54	33.2	53.48	-2.16	389.2	398.2	5.0	2.2	GREATER MANCHESTER	2+
2002	11	9	23	36	42.7	53.48	-2.16	389.5	398.3	5.0	2.0	GREATER MANCHESTER	
2002	11	10	4	12	22.6	53.49	-2.22	385.3	399.4	5.0	2.3	GREATER MANCHESTER	3+
2002	11	10	11	43	54.7	53.48	-2.17	388.6	398.4	5.0	2.0	GREATER MANCHESTER	
2002	11	10	18	47	9.5	53.49	-2.22	385.3	399.4	5.0	2.0	GREATER MANCHESTER	
2002	11	13	18	22	48.3	61.25	2.83	658.7	1273.0	10.8	2.7	NORTHERN NORTH SEA	
2002	11	16	4	57	46.7	53.49	-2.17	389.0	399.3	5.0	2.1	GREATER MANCHESTER	2+
2002	11	16	4	59	1.9	53.48	-2.18	388.1	398.6	5.0	2.5	GREATER MANCHESTER	3+
2002	11	16	7	34	36.9	53.50	-2.21	386.4	400.5	5.0	2.1	GREATER MANCHESTER	
2002	11	19	1	0	31.0	53.49	-2.19	387.5	399.4	5.0	2.1	GREATER MANCHESTER	2+
2002	11	19	21	15	56.4	49.19	-2.08	394.2	-78.5	13.1	2.5	JERSEY-CHANNEL ISLANDS	3+
2002	11	22	1	40	22.0	53.03	2.74	717.6	358.5	5.0	3.1	SOUTHERN NORTH SEA	
2002	12	1	9	37	5.0	53.26	-0.88	474.7	373.8	1.0	2.2	WORKSOP-NOTTS	
2002	12	28	14	36	3.2	51.71	-2.86	340.5	201.4	25.9	2.4	USK-GWENT	
2002	12	30	1	59	23.6	54.36	-3.09	329.5	497.1	11.6	2.0	CONISTON-CUMBRIA	

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BGS Seismology reports

IR/02/53 Walker, A.B. UK Earthquake monitoring 2001/02, BGS Seismic Monitoring and Information Service, Thirteenth Annual Report. June 2002.

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UK EARTHQUAKE MONITORING 2001/02 BGS SEISMIC MONITORING AND INFORMATION SERVICE: THIRTEENTH ANNUAL REPORT

A B Walker

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 Department of Transport Local Government and the Regions (DTLR) with major financial input from the Natural Environment Research Council (NERC). This Customer Group is listed in Annex A.

In the 13th year of the project (April 2001 to March 2002), nine networks were upgraded with the installation of QNX operating systems and a strong motion instrument was installed at Hartland in North Devon. Some gaps still remain in station coverage; notably in Northern Ireland. Other areas with site-specific networks, in Jersey, northern Scotland, the Outer Hebrides and the Orkney Islands, remain vulnerable to closure owing to their dependency on funds from the commissioning bodies.

Some 135 earthquakes were located by the monitoring network in 2001, with 37 of them having magnitudes of 2.0 ML or greater and 16 reported as felt. Six strong-motion records were captured from five of the eighteen sites now equipped with strong motion instruments. The largest earthquake in the reporting year on 28 October was widely felt in central England, had a magnitude of 4.1 ML, with an epicentre near Melton Mowbray. A macroseismic survey was conducted and around 6,500 replies were received, giving a maximum intensity of 5 on the European Macroseismic Scale (EMS, Annex H). The earthquake was felt up to 140 km away and over an area of 25,000 km^2 (Isoseismal 3). The nearest 3-component strong motion instrument to record the earthquake was 15 km from the epicentre and accelerations of 121, 190 and 212 mms^{-2} were recorded for the vertical, NS and EW components, respectively. The focal mechanism indicates oblique normal faulting along either a near N-S fault plane dipping at 51° or along a near E-W fault plane dipping at 58°. The largest offshore earthquake occurred in the central North Sea on 7 May 2001 with a magnitude of 5.0 Mw, approximately 410 km east of Edinburgh. It was felt on three nearby oil platforms in the Ekofisk field. The Ekofisk Hotel Platform control tower described "a swaying lasting 2 minutes which left us feeling dizzy", they also confirmed that the Albuskjell platform, some 15 km to the north and the Eldfisk platform, some 26 km to the south, reported similar felt effects. The focal mechanism obtained for the earthquake shows normal faulting with north-south trending nodal planes. In addition to earthquakes, BGS frequently receives reports of seismic events felt and heard, which on investigation prove to be sonic booms, spurious or in coalfield areas, where much of the activity is probably induced by mining. During the reporting period, data from four sonic events were processed and reported upon following public concern or media attention.

All significant felt events and some others were reported rapidly to the Customer Group through seismic alerts sent by e-mail. The initial alert was followed by a more detailed information release. The alerts were also published on the Internet (http://www.gsrg.nmh.ac.uk). Monthly seismic bulletins were issued 6 weeks in arrears and, following revision, were compiled into an annual bulletin (Simpson, 2002). In all these reporting areas, scheduled targets have been met or surpassed.

The environmental monitoring stations at Eskdalemuir and Hartland observatories recorded a variety of parameters throughout the year and the data are now accessible on-line through an Internet connection.

WIZMAP II ISC EDITION: USER'S GUIDE

R M W Musson

The program Wizmap II is a software tool for viewing and analysing earthquake catalogue data, in wide use around the world. It provides some of the functionality of a GIS, but tailored specifically to common seismological tasks, and without the steep learning curve that many commercial GIS systems have. The ISC edition is specially tailored to handle the feature-rich, extensible ISF data format used by ISC for distribution of earthquake data. This new version of Wizmap II can read and write such files, and can be used to merge or extract earthquake data according to a variety of criteria, as well as performing a number of routine analysis tasks such as *b*-value analysis, depth cross sections, and so on.

BULLETIN OF BRITISH EARTHQUAKES 2002

B Simpson (editor)

There were 235 earthquakes located by the monitoring network during the year, with 87 of them having magnitudes of 2.0 ML or greater. Of these, 42 are known to have been felt, together with a further 6 smaller ones, bringing the total to 48 felt earthquakes in 2002.

The largest onshore earthquake occurred on 22 September some 3 km northwest of Dudley, at a depth of 14 km, with a magnitude of 4.7 ML. It was felt over an area of 126,000 km^2 (isoseismal 3) and BGS were inundated with reports about the earthquake. Many media interviews were given and a macroseismic survey questionnaire was published both online and in the Daily Telegraph newspaper. Approximately 6,300 electronic reports were completed with a further 1,900 from the Daily Telegraph. BGS received reports of electric power being cut off to many homes in districts of Birmingham and multi-storey flats were evacuated in the Egbaston district of Birmingham. The earthquake was felt from the west coast to the east coast, as far north as Lancashire, West Yorkshire and Humberside and to Dorset and Kent in the South. The highest observed intensity was 5 EMS, which was observed quite widely over an area around Dudley, Birmingham, Walsall and Wolverhampton and as far south as Kidderminster and Bromwich. In a number of cases, mirrors and clocks were thrown off walls, a bookcase fell over, large items of furniture shook violently and there was a high level of alarm amongst the local population. A few reports mentioned children being thrown out of their beds. A maximum acceleration of 0.015g was measured at the strong motion station at Keyworth, some 82 km from the earthquake. The focal mechanism for the Dudley earthquake shows strike-slip faulting along either near north-south or east-west fault planes. The average maximum compressive stress direction has an azimuth of 323°and dip of 5° and the minimum stress direction strikes at 233° and dips at 9°. Two aftershocks were recorded, with magnitudes of 2.7 and 1.2 ML on 23 and 24 September respectively. The larger of the two aftershocks was felt with an intensity of 3 EMS.

he largest offshore earthquake occurred in the Northern North Sea on 14 February, with a magnitude of 4.0 ML. It was located approximately 210 km east of Lerwick, Shetland Islands. A further 14 events occurred in the North Sea and surrounding waters during the year, with magnitudes ranging between 1.5 and 3.5 ML.

A magnitude 3.0 ML earthquake occurred on 12 February near Bargoed, Mid Glamorgan. BGS received reports from residents of Bargoed, Pontypridd, Bridgend, Penpedairheol and Blackwood. These described, "the house shook violently", "the furniture shook", "the windows vibrated" and "we ran into the street", indicating an intensity of 4 EMS. A further 5 events were detected in the Bargoed area throughout 2002 with magnitudes ranging from 1.4–2.5 ML. This is an area that has experienced many seismic events in the past. The events in 2002 locate in the same area as events on 10 and 18 October 2001, with magnitudes of 3.1 & 2.5 ML, respectively, that were felt with intensities of 4 EMS. The focal mechanism obtained for the Bargoed earthquake shows normal/oblique normal faulting along either a north-south fault plane dipping sharply west or a NNW-SSE fault plane, dipping ENE.

A magnitude of 2.3 ML earthquake occurred on 2 May, near Loch Lochy, Highland Region. A single report was received from a resident of Spean Bridge, who described "the whole house shook", "the windows rattled" and "felt a shudder", indicating an intensity of 3 EMS.

Near Shiel Bridge, Highland, five earthquakes occurred with magnitudes ranging from 0.9 – 2.3 ML, three of these earthquakes with magnitudes of 2.3, 2.0 and 1.4 ML, occurred on 3 May. Felt reports were received for all three of these earthquakes from the village of Mallaig, where intensities reached 3 EMS. Felt reports described, "I felt a shudder through my feet" and "sounded like a large explosion".

A magnitude 2.9 ML earthquake occurred on 20 June, near Cardiff, South Glamorgan. Felt reports were received from residents of Cardiff and Caerphilly where intensities reached 3 EMS. Felt reports described "the furniture moved" and "both the chairs moved for a few seconds". The focal mechanism obtained for this earthquake shows normal faulting along a northwest-southeast fault plane, dipping either northeast or southwest.

On 1 August, an earthquake with a magnitude of 1.7 ML, occurred near Blackford, Tayside. BGS received a single report from a resident of Blackford, which described, "the bed shook and I was woken from sleep", indicating an intensity of 3 EMS. A further three earthquakes with magnitudes of 1.3, 1.0 and 0.4 ML, occurred in the Blackford area during 2002. This is an area that has continued to be active in recent years; 49 events occurred in 1997, of which five were felt by local residents; 10 events occurred in 1998, of which 2 were felt by local residents, 3 events occurred in 1999, 4 events occurred in 2000, of which 3 were felt and 3 events occurred in 2001, of which all were felt**.** These are all in the same general area as the magnitude 3.2 ML Ochil Hills earthquake in 1979, which had a maximum intensity of 5 EMS.

An earthquake with a magnitude of 1.3 ML, occurred near Dumfries, Dumfries and Galloway, on 9 October. BGS received a single report for this earthquake from a resident of Tinwald which described, " I felt a slight shudder" indicating an intensity of 2 EMS.

Five events occurred throughout the year, near Mallaig Highland region, with magnitudes ranging from 0.4 – 1.9 ML. BGS received no reports of these earthquakes being felt.

A magnitude of 4.5 ML earthquake occurred in northwest France on 30 September. BGS received many felt reports from residents throughout Jersey and Guernsey. These reports described "whole house shook", "a loud rumble", "cracking sound", "everyone woke up", "furniture moved" and "the bed shook", indicating an intensity of 4 EMS.

One hundred and sixteen earthquakes were located in the Manchester area during 2002 with magnitudes ranging from 1.3 – 3.9 ML. Thirty-six of these events were reported felt to BGS with intensities ranging from 2-5 EMS. The largest earthquake of the sequence occurred in central Manchester, on 21 October at 11:42 (UTC), with a magnitude of 3.9 ML. This was closely followed 22 seconds later by a magnitude 3.5 ML earthquake in the same locality. BGS received numerous felt reports about this earthquake swarm and a large number of phone calls. Many media interviews were given and a macroseismic survey questionnaire was published online. To date, BGS has received approximately 3000 reports via email. The earthquake together with several others in the swarm, were felt throughout Greater Manchester, up to distances of approximately 30 km. There have been reports of minor damage to buildings in the central Manchester area, indicating an intensity of 5 EMS.

On 19 November, an earthquake with a magnitude of 2.4 ML, occurred on Jersey, Channel Islands. BGS received felt reports from residents throughout Jersey, which described "items on the desk rumbled and we felt something rumbling in the ground" indicating an intensity of 3 EMS. This event is the largest in the general area since the magnitude 3.5 ML St Aubin's Bay earthquake on 30 April 1990, which was felt with intensities of 5 EMS.

In North Wales, two events on 1 June and 1 July with magnitudes of 0.7 ML and 0.2 ML, respectively, occurred on the Lleyn Peninsula, in the same area and at similar depths (20 km) as the magnitude 5.4 ML Lleyn earthquake of 19 July 1984, which was felt throughout England and Wales and into Scotland and Ireland.

The coalfield areas of Yorkshire, Nottinghamshire and West Glamorgan continued to experience shallow earthquake activity that is believed to be mining induced. Some 11 coalfield events, with magnitudes ranging between 1.0 and 2.2 ML, were detected during the year.

SEISMOGENESIS AND THE STATE OF STRESS IN THE UK FROM OBSERVATIONS OF SEISMICITY

B. J. Baptie

Studies of the focal depths of naturally occurring earthquakes across the British Isles show that the seismogenic thickness of the earths crust varies significantly with area. Focal depths in Scotland, Cumbria and Cornwall are found to be shallow (less than 15 km), whereas those in North Wales are deeper (15-25 km). The shallow nucleation depths observed in Cornwall and Cumbria are consistent with the observed high surface heat flows related to igneous intrusions and an inferred high geothermal gradient. By contrast, the deeper nucleation depths observed in North Wales suggest a lower geothermal gradient. Such a well-defined spatial variation in earthquake focal mechanism data is less apparent. An estimate of the state of stress is made using an inversion method to look for the best-fitting stress tensor that lies in the overlap between the families of stresses associated with a population of focal mechanisms for earthquakes in the UK instrumental database. This gives an estimate of both the orientations and relative magnitudes of the principle stress directions. The principal compression is found to be in north-northwest south-southeast direction. This result in consistent with expected stress associated with tectonic plate motion, mainly ridge-push from the Mid-Atlantic. The axes of maximum and minimum compression (P and T), though well constrained in azimuth are not so well constrained in dip. This is reflected in the calculated measure for the relative stress magnitudes.

STATE OF STRESS IN THE UK FROM OBSERVATIONS OF LOCAL SEISMICITY

B.J. Baptie

A good understanding of the regional stress tensor is required for a complete understanding of current geotectonic processes. First order plate motions in northern Europe result in compression of the UK from the northwest. Superimposed on the regional compression is the effect of uplift in the northwest of the UK due to glacial rebound with a peak rate of approximately 2 mm/year. At the same time the southeast of the UK is sinking relative to mean sea level. Focal mechanisms for local earthquakes in the UK show a mixture of strike-slip, thrust and normal faulting. Strike slip motion might suggest that tectonic stress is dominant, while thrust faulting is consistent with glacial rebound origin. The axes of maximum and minimum compression (P and T) for all fault plane solutions are found to be well constrained in azimuth though not so well constrained in dip. An estimate of the state of stress is made using an inversion method to look for the best-fitting stress tensor that lies in the overlap between the families of stresses associated with a population of focal mechanisms for earthquakes in the UK instrumental database. This gives an estimate of both the orientations and the relative magnitude of the principle stress directions, assuming that stress is approximately homogeneous within the region of interest. The principal compression is found to be in north-northwest south-southeast direction. This result in consistent with expected stress associated with motion of the major tectonic plates, mainly ridge-push from the Mid-Atlantic. The results are also consistent with stress directions found from other methods such as borehole breakouts and hydro-fractures.

THE FIELD INVESTIGATION TEAM OF THE ESC: PROPOSALS AND PRESENT PROGRESS

I Cecić and R M W Musson

FITESC is the acronym for the Field Investigation Team of the ESC (Musson et al, 2001). It is not a new idea to form an international team, which would collect, and later evaluate, macroseismic data for strong and damaging earthquakes in Europe and the Mediterranean. But after recent events in the 1990s (such as Southern Croatia, 1996, Central Italy, 1997, NW Slovenia, 1998, and especially Turkey and Greece, 1999), the absence of such a team was keenly felt, and discussions of this subject were re-opened. It was obvious that the seismological community currently lacks the mechanism for creating such a team. But if such an activity could be promoted, it would be possible to have a public homogeneous database of earthquake effect data, a valuable resource for many studies. Having such a team would also make an important improvement to the present level of co-operation and exchange of information in the Euro-Mediterranean region. At the General Assembly of the ESC in Lisbon, Portugal in 2000 a resolution was endorsed, in which an interest in creating such a team was expressed. A Preliminary Committee was formed, with aim to explore the possibilities of making this idea a reality.

SEISAN EARTHQUAKE ANALYSIS AND SEISNET NETWORK AUTOMATION SOFTWARE

J. Havskov and L. Ottemöller

In seismology, a wealth of data acquisition and processing systems are available, and a seismic observatory typically uses several systems for both data acquisition and processing and perhaps yet another system for research-related tasks. A common problem is the lack of a proper database structure, which prevents effective use of the data. The goal of SEISAN and SEISNET is to automate data retrieval from different data acquisition systems, whether local or remote, through SEISNET and provide a common platform for data processing and storage through SEISAN. The two systems are integrated so that SEISNET collects data directly into the SEISAN database and uses SEISAN programs for preliminary processing. Both SEISAN and SEISNET rely heavily on public domain software, and both can be described as a system to integrate known programs and data acquisition systems into a common system. The software packages (source code only) are in the subfolder for Chapter 85.6 on the attached Handbook CD.

MAXIMUM EARTHQUAKE MAGNITUDES IN THE AEGEAN AREA CONSTRAINED BY TECTONIC MOMENT RELEASE RATES

G Ch Koravos, I G Main, T Tsapanos and R M W Musson

Seismic moment release is usually dominated by the largest but rarest events, making the estimation of seismic hazard inherently uncertain. This uncertainty can be reduced by combining long-term tectonic deformation rates with short-term recurrence rates. Here we adopt this strategy to estimate recurrence rates and maximum magnitudes for tectonic zones in the Aegean area. We first form a merged catalogue for historical and instrumentally recorded earthquakes in the Aegean, based on a recently published catalogue for Greece and surrounding areas covering the time period 550 BC-2000 AD, at varying degrees of completeness. The historical data are recalibrated to allow for changes in damping in seismic instruments around 1911. We divide the area up into zones that correspond to recent determinations of deformation rate from satellite data. In all zones we find that the Gutenberg-Richter (GR) law holds at low magnitudes. We use Akaike's information criterion to determine the best-fitting distribution at high magnitudes, and classify the resulting frequency-magnitude distributions of the zones as critical (GR law), subcritical (gamma density distribution) or supercritical ("characteristic" earthquake model) where appropriate. We determine the ratio η of seismic to tectonic moment release rate. Low values of η (<0.5) corresponding to relatively aseismic deformation, are associated with higher *b* values (> 1.0). The seismic and tectonic moment release rates are then combined to constrain recurrence rates and maximum credible magnitudes (in the range 6.77.6 Mw where the results are well constrained) based on extrapolating the short-term seismic data. With-current earthquake data, many of the tectonic zones show a characteristic distribution that leads to an elevated probability of magnitudes around 7, but a reduced probability of larger magnitudes above this value when compared with the GR trend. A modification of the generalized gamma distribution is suggested to account for this, based on a finite statistical second moment for the seismic moment distribution.

A POWER-LAW FUNCTION FOR EARTHQUAKE INTERARRIVAL TIME AND MAGNITUDE

R M W Musson and T Tsapanos

The problem of time-dependent seismic hazard models is still an open one. While most hazard studies assume stationarity of seismicity, there has been some debate on the relative merits of Poissonian and non-Poissonian recurrence models, and opinions about the viability of the seismic gap hypothesis also vary. Previous attempts to treat seismic hazard as time-dependent have, however, concentrated on large earthquakes, which do not always control the hazard at a site. In this study, earthquake inter-arrival times are studied for several regions in Japan and Greece. It is found that a log-normal distribution provides a good model and that seismicity can be represented by the equation $\ln IAT = a + b M \pm c$ where ln IAT is the log inter-arrival time of earthquakes exceeding magnitude M and a, b and c are regional constants. This power law is clearly related to the normal Gutenberg-Richter magnitude-frequency law, but actually contains more information. This law provides a basis for time-dependent seismic hazard analysis in which the whole earthquake catalogue is used rather than just the largest events. A question still remains as to whether c (the standard deviation) is significantly dependent on magnitude.

EFFECTIVE PEAK ACCELERATION AS A PARAMETER FOR SEISMIC HAZARD STUDIES

R M W Musson

Pga has long been recognised as a poor parameter to express ground motion because of the way in which even quite small earthquakes can generate high peak accelerations in the form of low-energy spikes which actually have no serious implications for engineered structures. This means that earthquake hazard expressed as pga may not be realistic in terms of actual potential for damage. Effective peak acceleration (epa) is a concept proposed first by Newmark over 20 years ago as a replacement for peak ground acceleration (pga) as a hazard parameter. The use of epa is one way to circumvent the problem by using a normalised mean of spectral accelerations in the range of periods most of concern to engineered structures. The resulting epa value can be used to anchor a standard spectrum in the same way as has often been done with pga values. Epa has been the recommended reference parameter of earthquake ground motion in most major building codes, including the Uniform Building Code and Eurocode 8. However, this has not been matched so far with an equivalent use of this parameter in seismic hazard studies. This paper reviews the methods that have been used to calculate epa hazard and demonstrates some of the implications of replacing pga with epa.

HISTORICAL EARTHQUAKES OF THE BRITISH ISLES

R M W Musson

The British Isles are a moderate to low seismicity area, in which earthquakes do not present an everyday hazard, but are sufficiently frequent to require consideration with respect to sensitive structures. Since modern instrumental monitoring of British earthquakes only began around 1970, and classic seismometers of (for example) the Milne-Shaw type were insensitive to small local shocks, historical research into British seismicity has been essential for establishing an adequate earthquake catalogue, even for the early and middle years of the 20th Century. However, the historical data are actually rather good. The earliest recorded events in monastic annals go back even to the 7th Century, although accounts of most Medieval earthquakes tend to be lacking in sufficient details to enable reliable quantification to be done. The historical record improves very considerably in 1700 with the introduction of local newspapers, which means that (except for remoter areas) about 300 years of reasonably complete and reliable earthquake data exist for the purposes of hazard calculation or related studies. The continued practice of macroseismic monitoring of modern British earthquakes means that a good data set can be established for calibrating macroseismic methods of earthquake parameter determination; the parameters of historical British earthquakes that have been derived can therefore be treated with confidence.

MACROSEISMOLOGY

R M W Musson and I Cecić

Macroseismology is the oldest branch of seismology, and deals with the study of the felt effects of earthquakes, including damage. Prior to the development of reliable seismometers, this was the only way in which earthquakes could be studied. Subsequently, especially in the 1950s and 1960s, this form of study went to some extent into decline. More recently, the importance of macroseismology has been restated in the context of the revaluation of historical seismicity, and in studies of seismic hazard and risk. This chapter of the IASPEI Centenary Handbook on Earthquake & Engineering Seismology surveys the whole field of macroseismology, and the methods and techniques available.

THE FELT EFFECTS OF THE CARLISLE EARTHQUAKE OF 26 DECEMBER

R M W Musson and P H O Henni

The earthquake of 26 December 1979, with an epicentre north of Carlisle, near Longtown, Cumbria, was one of the most significant British earthquakes of the second half of the 20th century. It had a magnitude of 4.7 ML and was felt over an area of around 84,000 km2 at intensity 3 EMS, covering most of Central Scotland, the Borders, Cumbria and the North East of England. It was the mainshock of a sequence of around 90 events recorded by the British Geological Survey (BGS), then the Institute of Geological Sciences (IGS), UK seismic monitoring network. BGS undertook a macroseismic (felt effect) survey for the mainshock, with around 4,000 usable responses received, and also for the two largest aftershocks, which occurred on 1 January 1980 and 13 December 1980, both with magnitude 3.8 ML. The results of these surveys have not been published until now. The highest intensities were reached around the Carlisle and Longtown areas, where 6 EMS was assigned from reports describing chimney stack and roof damage, with debris falling into the street, cracks in walls and other similar effects. Macroseismic estimates of the parameters of the earthquake agree well with the instrumental parameters so far as epicentre and magnitude are concerned, but there is a significant discrepancy with respect to depth. Also, although the size of the felt area is consistent with what is expected from average UK intensity attenuation, there is a marked directionality to the energy release, resulting in the earthquake being much more perceptible to the north than to the south.

POTENTIAL FOR APPLICATION OF PSInSAR DATA FOR TECTONIC MODELLING IN SUBDUCTION AREAS

R M W Musson, J J Bommer, M Haynes and A Ferretti

Interest has been increasing over the last few years in the use of satellite radar interferometry data (InSAR) for applications in seismology and tectonics. We report here on a new technique, PSInSAR, which relies on permanent scatterers and offers the possibility of measurements of ground displacements to a degree of accuracy, and over periods of time, previously unobtainable from conventional interferometry. This technique has been developed by TeleRilevamento Europa of the Politecnico di Milano in Italy. A permanent scatterer is any large, permanent angular object, such as building roofs, metallic structures, and even large boulders. Using these data, very accurate displacement histories can be obtained for the period 1991 to the present. Calibration with GPS data show good agreement, but the PSInSAR data are less noisy. The effect is akin to suddenly having a very dense GPS network retrospectively available for the last ten years in any moderately urbanised area in a region for which a satellite data archive exists (about 50% of the globe). Data have been gathered for the area around Suruga Bay, Japan, which is expected to be the locus of a future great Tokai earthquake. Previous studies have used levelling or GPS data to model the locked part of the subduction plane in this area, using the Akaike Bayesian Information Criterion (ABIC) method. This method could be used with PSInSAR data, which would be likely to yield a better result on account of the greater density of data. Furthermore, there is now the potential to use the ABIC method in any subduction area, whether there exist GPS/levelling data or not, provided only that the area is sufficiently urbanised to yield adequate permanent scatterers as data points. This work results from a European Space Agency (ESA) 'Earth Observation Market Development' project entitled 'Developing markets for EO-derived land motion measurement products', involving, NPA (lead), the British Geological Survey (UK), Imperial College (UK), TeleRilevamento Europa (Italy), ImageONE (Japan), the Geographic Survey Institute (Japan), Oyo Corporation (Japan), Fugro (Netherlands) and SARCOM (ESA data distributing entity).

THE SIGNIFICANCE OF ABSENT EARTHQUAKES: WHAT IS THE WEIGHT OF A HISTORIAN'S OPINION?

R M W Musson

The level to which a historical earthquake catalogue is considered complete is one of the requirements of a seismic hazard analysis; seismic activity rates cannot be estimated from a catalogue alone without knowing about the completeness in terms of magnitude and date thresholds. A number of statistical tools have been proposed, and are sufficiently well known that, to some extent, this subject is now viewed as routine. However, in areas of relatively low seismicity, statistical methods may be difficult or impossible to use, and completeness has to be judged using a historical assessment of source materials. The critical question becomes, "Given the state of historical writing for a given place and time, what is the magnitude threshold (if any) for which we can be certain that any earthquake above this threshold must have been recorded"? Answering this question in an objective way proves to be difficult. It is an extremely historical question, because any approach to it raises fundamental questions about the nature of the sources themselves. And yet it is also a rather practical question, since the answer may have a significant effect on the hazard value that a design engineer will ultimately have to work to. Experience shows that, all other things being equal, two different judgement calls by historians on the quality of source materials can change the final hazard value at a site by around 5 to 10%. This is enough of a difference to make it worthwhile to devote some scrutiny to how these opinions are derived. In this study, the questions raised and the possible significance of the answers are explored in the context of the early seismicity of the British Isles.

EKOFISK SEISMIC EVENT, MAY 7, 2001

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

On May 7, 2001, a seismic event was strongly felt at the platforms in the Ekofisk oil field, which is located within the Central Graben in the Norwegian sector of the North Sea. The felt reports indicated that even heavy objects moved and that it was difficult to stand upright. A macroseismic intensity of VI-VII (EMS98) was assigned to the platforms in the central part of the Ekofisk field. The event was recorded on seismic stations in most parts of Europe up-to distances of 2500km. The event was analysed using the large amount of regional seismic stations available, and the epicentre was determined at 56.565ºN and 3.182ºE, with an error of about 5km in both directions. The magnitudes determined were M_W=5.0, M_b=4.4 and M_S=4.6, and thus the event was the largest in the region in over 30 years. The main difficulty in the analysis was that no data from close distances were available, since the closest station was more than 300 km from the epicentre. In order to examine if and how the event was related to the hydrocarbon extraction at Ekofisk, knowledge of the hypocenter depth is essential but the lack of near-by stations precludes its direct determination. The seismograms were dominated by long-period surface waves while the body waves showed emergent onsets which, possibly, indicate a shallow source in relatively soft rocks. Due to the emergent onsets, it was not possible to determine the focal mechanism based on first motion polarities. Instead, we carried out a moment tensor inversion (procedure in which the complete waveforms are inverted) in order to resolve the source mechanism, but also to obtain an estimate of the source depth. This yielded a normal faulting solution with north-south trending nodal planes. A best fit between observed and synthetic waveforms was obtained for a shallow hypocenter depth of less than 5 km. A final conclusion on the relation between the event and hydrocarbon extraction at Ekofisk has not yet been made. A source depth above the reservoir (3km), where there are potential faults, could possibly be related to stress changes due to ongoing hydrocarbon extraction, water flooding of the reservoir and drill cuttings re-injection into the overburden. However, there are active deep faults in the region that can generate earthquakes of this size and, with the present evidence, a deeper tectonic source cannot be ruled out.

MOMENT MAGNITUDE DETERMINATION FOR LOCAL AND REGIONAL EARTHQUAKES BASED ON SOURCE SPECTRA

L. Ottemöller and J. Havskov

We investigated the use of an automated routine to determine moment magnitudes from the displacement spectra of local and regional earthquakes. Two algorithms, a genetic algorithm and a converging grid search, were developed and tested with earthquake data from Mexico, Norway, and Deception Island (Antarctica). It was found that compared with manual analysis, the algorithms give reliable automatic moment magnitude (M_w) estimates in the range $-1 < M < 8$. The converging grid search appeared to be more cost-effective than the genetic algorithm. M_w at local and regional distances seems superior to amplitude-based magnitudes that saturate for large earthquakes. The application of the automated algorithm in near real time may help to obtain a nonsaturated magnitude estimate in the case of a large earthquake immediately after the earthquake has occurred. Also, the method can be useful for processing large amounts of data.

AUTOMATED MOMENT MAGNITUDE DETERMINATION

L. Ottemöller

The moment magnitude at local and regional distances seems superior to amplitude-based magnitudes that saturate for large earthquakes. Therefore, an automated procedure based on a genetic algorithm to determine the moment magnitude from the displacement spectra of local and regional earthquakes was developed. The method was tested with earthquake data from Mexico, Norway and the Deception Island (Antarctica). It was found that the algorithm gives reliable moment magnitude estimates in the range $-1 < M_W < 7$, compared to manual analysis as well as compared to other magnitude scales. The application of the automated algorithm in near-realtime may help to obtain a realistic size estimation in case of large earthquakes shortly after earthquake occurrence.

A METHOD FOR BAYESIAN ESTIMATION OF THE PROBABILITY OF LOCAL INTENSITY FOR SOME CITIES IN JAPAN

T Tsapanos, O Ch Galanis, G Ch Koravos and R M W Musson

Seismic hazard in terms of probability of exceedance of a given intensity in a given time span, was assessed for 12 sites in Japan. The method does not use any attenuation law. Instead, the dependence of local intensity on epicentral intensity IO is calculated directly from the data, using a Bayesian model. According to this model (Meroni et al., 1994), local intensity follows the binomial distribution with parameters (I., p). The parameter p is considered as a random variable following the Beta distribution. This manner of Bayesian estimates of p are assessed for various values of epicentral intensity and epicentral distance. In order to apply this model for the assessment of seismic hazard, the area under consideration is divided into seismic sources (zones) of known seismicity. The contribution of each source on the seismic hazard at every site is calculated according to the Bayesian model and the result is the combined effect of all the sources. High probabilities of exceedance were calculated for the sites that are in the central part of the country, with hazard decreasing slightly towards the north and the south parts.

THE DUDLEY AND MANCHESTER UK EARTHQUAKES

Alice Walker and Chris Browitt

Earthquakes can occur anywhere in the world, although they are not uniformly distributed, with the majority at boundaries of the great plates that make up the outer skin of the earth and which move at about the speed our fingernails grow, driven from below. Globally, there are around 800 'moderate' earthquakes, (magnitude 5 to 5.9 Ms), 120 'strong' ones (magnitude 6 to 6.9) and around 20 'major' earthquakes, of magnitude 7 or greater, each year. There are many more smaller ones; some 70,000 reported internationally in 2001, but most were unknown except to the seismologists who study them. The main hazards during and following a larger earthquake include ground shaking, landslides, tsunamis and ground liquefaction. Fires may rage due to ruptured gas or water mains, and access for emergency services may be blocked. The great fire in San Francisco following the 1906 earthquake, lasted three days and was more damaging than the shaking itself. Firestorms after the 1923 Tokyo earthquake, killed over 38,000 people. Recent fatal earthquakes in El Salvador and India, on 13 January and 26 January, 2001 (both magnitude 7.7 Mw) killed 800 and 20,000 people, respectively.

The Italian earthquake on 31 October 2002, which killed 26 schoolchildren and teachers, was of modest size; with a magnitude of 5.6 Ms, 5.9 Mw; there are about 270 of this size or greater each year, worldwide. At BGS, it was realised within an hour or so (as soon as the magnitude was calculated) that this earthquake was too small to have caused any well-constructed buildings to collapse, as was being suggested in early reports. TV images the next day showed the extent of the destruction of the local school and the minimal damage elsewhere, clearly demonstrating poor quality construction and revealing a tragedy which should never have happened.

In the UK, we are not immune from earthquakes experiencing around 200 each year with about 20 felt by local residents (Fig 1). The largest, in 1931, to affect the United Kingdom was centred on the Dogger Bank; fortunately, 100 km out in the North Sea. It had a magnitude of 6.1 ML and caused minor damage on the east coast of England where many chimneys fell down. Onshore, the largest earthquake in the last 140 years, occurred in North Wales on 19 July 1984 with a magnitude of 5.4 ML. It was felt over most of England, throughout Wales and even into Scotland and Ireland. It caused some damage as far as Liverpool, 120 km from its epicentre. More recently, an earthquake with a magnitude of 4.2 ML near Warwick on 23 September 2000 and another near Melton Mowbray in October 2001 (magnitude 4.1 ML) were felt over much of England and Wales. There were many reports of objects such as ornaments, pictures or toys falling or being displaced. In a few cases, heavy objects, including washing machines, cookers and lounge furniture were also said to have moved, but no damage was reported.

The third large earthquake to strike central England in the space of 2 years was centred on Dudley, in the West Midlands, on 23 September 2002 (BST), with the larger magnitude of 4.7 ML (8-11 times bigger in energy than the previous two). Again, people were awakened over a wide area and the felt effects stretched from Dublin, Ireland to the east coast of England and from Yorkshire to the south coast and Devon. In the epicentral area, there was much alarm and some damage to chimneys and roofs (Fig 2), with plaster cracking on interior walls, indicating a maximum intensity of 6 on the European Macroseismic Scale (which describes the degree of shaking in an earthquake). Information on these effects has been gathered through some 8000 responses to BGS questionnaires distributed nationwide through the media and internet. Some typical felt reports were "I woke up frightened and clinging to my bed! I thought that the roof was going to come down on me, I didn't realise that it was an earthquake but there seemed to be a lot of noise above me in the loft and some banging"; "The bottles on our shelf started rattling violently, and then the whole room started moving from side to side"; "I was sitting at my computer when the whole house started to shake violently. I could see walls and ceiling moving also kitchen wall cupboards. My computer screen was shaking and I could feel the floor heaving beneath me"; "I was asleep and the whole house (located on top of a hill) shook for over 10 seconds. There was a deep disturbing rumbling/rattling noise all around me and I felt I was lying on top of a large oscillating jelly structure. I ran out the house to check what was happening but everything seemed normal and quiet"; "the whole of the house was shaken and my glass full of water smashed as it fell off the table". These descriptions are typical for larger earthquakes in the UK and for some smaller ones in the epicentral area. So far, there have been two reports of people injuring themselves as a result of rushing out of the house in alarm – one person broke their leg falling down stairs, another broke their toe. A map showing the felt area of the Dudley earthquake is given in Figure 3.

Shock waves from the Dudley earthquake were recorded across the UK on the BGS seismic monitoring network and throughout Europe. A seismogram of the ground movement and the different seismic waves recorded is shown in Figure 4. This was the largest earthquake to affect the UK since a magnitude 5.1 ML event near Shrewsbury in 1990 which was felt throughout England and Wales and caused some damage near its epicentre.

To put the Dudley earthquake into perspective: 1,300 earthquakes of this size or bigger occur each year somewhere in the world. However, in the UK we expect, on average, an earthquake of this size or bigger to occur once every eight years. So we might think that it will be another 8 years before the next large one, but statistics don't work like that, and the next 4.7 magnitude earthquake could occur tomorrow, next year or next century. Seismologists have not yet solved the problem of predicting earthquakes but with increasing objective data being collected they are constantly improving their assessments of how likely earthquakes are, and are able to inform engineers and planners accordingly.

Details of British and important global earthquakes are posted on the BGS seismology web site which is continually updated. During the Dudley earthquake some 360,000 hits were received on the day it occurred indicating the power of this medium for disseminating objective information.

Most recently, there has been a sequence of earthquakes in the Manchester area, with the highest magnitude being 3.9 ML. In the 5 weeks following this strongest shock on 21 October, some 106 earthquakes, with magnitudes between 1.1 and 3.9 have been located, with 36 reported to be felt. There has been no significant damage and most of the felt reports have been confined to the greater Manchester area, with a number of reports received up to 30 km away for the largest event. Some typical ones were "The whole building wobbled and shook producing a sensation of being disoriented" and "I could feel the ground shaking below my feet. Desks in the classroom were vibrating as well". These indicate that the maximum intensity experienced was 5 EMS (European Macroseismic Scale). Immediately after the first felt earthquakes, a temporary network of three seismometers was installed in the epicentral region. The addition of these new stations permits the depths of the events to be established more accurately, with the emerging result that they are shallow, between 2 and 4 km. This evidence fits well with the felt effects (small earthquakes felt over restricted areas), and shows that this is one of the shallowest sequences in the UK. At the time of writing (29 November, 2002) there have been no reports of felt earthquakes in the past 10 days, indicating that the activity has started to decline.

Earthquakes, both globally and in the UK, are monitored using the BGS seismic network of 146 seismometer stations. Data is transferred to Edinburgh four times a day (or on demand during periods of particular interest) using either dial-up telephone lines or the public internet. Within 1 to 2 hours, the location, magnitude and nature of an event (e.g. earthquake, explosion, sonic boom, or mining-induced seismicity) are determined and the results are widely disseminated. Interest from BGS' wide spectrum of customers in government, industry and academia, and from the media and the public is often intense. A 24-hour on-call service is operated, with computer connections between staff members' homes and the BGS Edinburgh office allowing rapid analysis. For more information visit www.earthquakes.bgs.ac.uk.

The National Seismological Archive (NSA)

The following Annex describes the status of the material from known major seismological observatories, i.e. excluding a few small amateur-run stations. All extant seismograms and bulletins from these observatories have been catalogued and the seismograms have all been microfilmed, with a backup copy set stored off site from the NSA, at BGS Keyworth.

Aberdeen: All material from the original Parkhill Observatory, Dyce (1914-1932) is presumed lost (one small photo of a 1924 seismogram is held). Seismograms and seismological bulletins from the Aberdeen Observatory, Kings College, Aberdeen University (1936-1967) are held in the NSA.

Bidston: Material from the Bidston Observatory, Liverpool (1898-1957) held in the archive consists of seismograms (1938-1956) and station bulletins (1901-1919, 1925-1940).

British Association for the Advancement of Science Seismological Committee Archive: The Seismological Committee of the BAAS was founded in 1841, and continued intermittently up until the 1980s. The surviving material relating to this committee was in the hands of Dr John Hudson, Cambridge University, who has now deposited the material with the NSA. It consists principally of copies of the annual reports of the committee (some printed, others in original typescript), together with material relating to the Milne-Gray Seismological Trust, a charitable fund established by John Milne (d. 1913) in his will, and extended by his friend Thomas Gray. This fund was created to support research into the physics of the earth. The administration of the fund has now been passed from the defunct BAAS Committee to the British Geophysical Association, which is a joint association of the Geological Society and the Royal Astronomical Society.

Cambridge: Material from the Crombie Seismological Laboratory, Cambridge consists of annual reports (1954-1968) and one bulletin (1958).

Coats Observatory, Paisley: Material held from this observatory (1898-1919) consists of seismograms (1900-1919 and 1931-1935) and a seismographic register (1902-1909).

Durham: Material held from the Durham University Seismological Observatory (1930-1975) consists of seismograms (1938-1975) and bulletins (1930-1975).

Edinburgh: Material from the Royal Observatory, Edinburgh (1894-1962) consists of seismograms (1902-1908) and bulletins (1922-1962). The archive holds a wider range of microfilmed seismograms (1896-1962) than originals, which were destroyed in the late 1960s.

Eskdalemuir: Material from the Eskdalemuir, Scotland Observatory (1908-1925) is varied, and consists of seismograms (1910-1920) and bulletins (1913-1916, 1920-1925).

Eskdalemuir WWSSN: The Eskdalemuir Worldwide Standard Seismograph Network seismograms (1964-1995) are stored at Eskdalemuir, with microfilm copies available for inspection in the NSA. More information on ESK WWSSN can be found in report WL/99/18.

Guildford: Material held from the Seismograph Station at Woodbridge Hill, Guildford consists of bulletins (1910-1915).

Jersey: Material from the Jersey Observatory (1935-1994) consists of seismograms (1936-1985) and bulletins (1946-1965).

Kew: Material from the Kew Observatory (1898-1969) consists of seismograms (1904-1965) and a range of bulletins (1899-1969), together with a wide range of related material.

Oxford: Material from the Oxford Observatory (1918-1947) are presumed lost, bar one seismogram held in the NSA; this record was borrowed by ATJ Dollar and never returned, which is how it escaped the fate of the bulk of the records. Two seismograms have been discovered on the Isle of Wight, amongst Milne material.

Rathfarnham: Material from the Rathfarnham Castle Observatory, Dublin (1916-1964), is held by the Dublin Institute for Advanced Science (DIAS). The NSA holds some bulletins (1950-1960).

Shide: Although most material from the Shide Observatory, Isle of Wight (1895-1917) was presumed destroyed, items remaining in the Isle of Wight County Record Office, Carisbrooke Castle Museum and in private hands have been examined and catalogued.

Stonyhurst: Material from the Stonyhurst College Observatory, Blackburn (1908-1947) is also presumed destroyed, except for some bulletins held in the NSA (1909-1933), and a single seismogram (for 7-8 March 1931) which exists as a photographic copy supplied to Bidston observatory at some point.

The Soil Mechanics UK Historical Data Archive: In 1981-2, Soil Mechanics Ltd was one of four organisations involved in extensive research into the history of British earthquakes, the other three being Principia Mechanica Ltd, British Geological Survey, and Imperial College London. The SML project led to the publication of a four-volume study of the history of British earthquakes, based around revaluation of 72 representative events. The material accumulated by this study has now been deposited with the NSA. It consists of three large boxes of materials, with folders for each of the earthquakes that were investigated, containing photocopies of source materials, working notes, etc. The intention is to preserve all this material in its present organisation, rather than attempting to merge it with similar data collected by BGS.

Valentia WWSSN: All records from this station are presumed to be held at Valentia, Ireland.

West Bromwich: The surviving papers and records from West Bromwich Observatory (JJ Shaw) are held at the Lapworth Museum, Birmingham University. The seismograms, bulletins and selected other material have now been microfilmed. One seismogram is held by the NSA; this record was discovered to have been used as a bookmark in a book purchased from a Midlands second-hand bookshop.

In addition to the above, mention can be made of the seismological activity at Fort Augustus. In 1947 ATJ Dollar installed a Jagger shock recorder at Fort Augustus Abbey; this instrument was formerly deployed at Dunira, near Comrie, and before that was used in Montserrat during the previous volcanic crisis to the recent one (in the 1930s). This instrument was poorly located in the Abbey (next to the back door) and never worked (except for recording the closing of the back door). Shortly before the Abbey closed last year, the instrument was donated to the NSA. Attempts are presently underway to restore the clock mechanism. So far as can be determined, this is the last Jagger shock recorder in existence. There are none surviving at Hawaii Volcano Observatory where the instruments were invented and manufactured.

External collaboration

Bristol University; Mapping seismic discontinuities

A study at Bristol University, under the leadership of George Helffrich, has been looking at reflectors under the Scottish Highlands with the deployment of broadband sensors.

The broadband deployment in the Scottish Highlands (RUSH, Reflectors Under the Scottish Highlands) ended in November, 2000. This network of nine broadband instruments was deployed to gather evidence for whether the offshore mantle reflectors reported by BIRPS (British Institutions Reflection Profiling Syndicate) off the north coast of Scotland extends under the Highlands. The wide frequency capabilities of these instruments are ideal for the two analysis techniques being used: teleseismic shear-wave splitting and teleseismic receiver function analysis. The October 1999 Hector Mines earthquake in southern California occurred during the deployment, which readily confirmed the reflector's presence under the Orkneys and the northern Scottish coast. These had been seen previously in short-period receiver function analysis of BGS network data from the seismograph station at Reay (ORE). The next phase will be to complete the teleseismic shear-wave splitting analysis of the data. This will provide key information to test two hypotheses of what the reflectors represent: large-scale shear zones in the crust, or a relic lithospheric slab left under Scotland after the end of Caledonian age subduction.

Brunel University; Glaciotec project

Glacio-isostatic rebound following the decay of the main British ice sheet has long been considered a trigger for palaeoseismic activity in northern Britain, but it is widely seen as a vestigial influence on contemporary seismic strain release. Brunel University's **Glaciotec** project, led by Dr Iain Stewart, is critical re-evaluating these views, in the context of a wider resurgence of interest in the effects of former ice sheets on ongoing crustal deformation and seismicity (Stewart *et al*. 2001). As new research from eastern North America and Fennoscandia highlights the subtle role that residual postglacial rebound plays in promoting ongoing crustal instability in deglaciated regions, seismologists are even concluding that rebound may be responsible for large historical earthquakes, such as the great 1811-1812 New Madrid, eastern USA. In the UK domain, recent studies conclude that, albeit on a more modest scale to that evident in Fennoscandia, the marked variations in the levels of seismicity around the former British rebound dome may reflect a glacio-isostatic component.

Ironically, the recognition that postglacial rebound may still exert a small but not insignificant influence on present-day UK seismicity patterns emerges as **Glaciotec** re-evaluates the evidence for significant 'endglacial' fault activity and seismicity. The **Glaciotec** project has undertaken a systematic appraisal of reported postglacial faults in the Scottish Highlands, and concludes that published accounts of large postglacial fault displacements are spurious, and instead are limited to metre-scale vertical movements (Firth & Stewart 2000-abstract listed in Annex G, Stewart *et al.* in press). With all the documented postglacial faults in the NW Highlands being considered as 'unproven', the Scottish case for a burst of major seismotectonic activity during deglaciation appears unconvincing. Rejection of major strike-slip postglacial movements, which are kinematically incongruous with the present-day crustal stress regime, also resolves the need to invoke large regional rotations of the Scottish stress field during the last few thousand years, as recently proposed by researchers at Edinburgh University.

To convincingly demonstrate significant past seismotectonic activity in the Scottish Highlands, future **Glaciotec** research aims to exploit an array of multi-disciplinary investigative practices. These practices, such as subsurface geophysical imaging, fault trenching, and palaeoenvironmental studies, are now routinely applied elsewhere in the low-seismicity intraplate domain of northern Europe. At the same time, however, resolving the subtle influence of glacial unloading on seimotectonic activity in the UK will also require improved focal mechanisms and *in situ* stress data, and detailed measurements of contemporary horizontal and vertical crustal motions. Without integrating these approaches, the UK's glacio-seismotectonic heritage will remain ambiguous.

Leicester University; UK velocity model

In the last decade, teleseismic receiver function analysis has become a powerful tool for investigating lithospheric structure. Conventionally, the method uses broadband seismic recorders, and models the derived receiver functions in terms of 1-D shear wave velocity models beneath the receiving stations. Recently, various authors (e.g. Yuan et al 1997) have shown that deconvolution of the instrument response from short period waveforms can provide stable crustal models able to resolve velocities and thicknesses of the major crustal layers.

The resulting seismic model of UK crustal structure will be used to constrain the long-wavelength modelling of the BGS UK gravity data base. Gross seismic velocity and density changes across boundaries will be interpreted in terms of crustal structure and composition and analysed in relation to the tectonic processes resulting in the present UK geological architecture. Residual pressure differences at depth derived from the density model will be examined in relation to present UK seismic activity.

Leeds University

Leeds and Bristol Universities’ broadband stations, which were co-located throughout the UK, with BGS short period instruments in July 1998, continued to operate until September 2000. The objective of the array is two-fold:

- An investigation of the Earth's core-mantle boundary region and the inner-core/outer core boundary.
- A prototype for a 3-component broadband seismic network in Britain.

Teleseismic events from around the world are used to image the lowermost mantle and inner core. South Pacific events are used to map the lower mantle scatterers and the inner core boundary. North-west Pacific events and Central American events are used to investigate D" reflections from discontinuities at the core-mantle boundary.

The data, along with that from other European arrays, has been used to map detailed variations in the morphology of the D" region beneath northern Asia using migration techniques. Data was also made available to BGS for analysis of significant UK earthquakes.

Stephen Arrowsmith (co-supervised by Leeds University and BGS), has been collecting P- and S-wave arrival data for 100 teleseismic events from Leeds broadband stations and the BGS short period seismograph stations, and testing tomographic inversion software provided by J VanDecar. The overall aim of the project is to create a 3D model of the structure beneath Britain at crustal and upper mantle depths.

A long standing question in Geophysics is to what degree are the crust and mantle coupled during orogenic deformation? Do surface expressions of structural geology reflect the structural geology of the mantle? Such issues are important for understanding the driving forces of plate tectonics and the shaping of continents. Tomographic images provide a picture of the underlying crustal and mantle structure, in much the same way as ultrasonic imaging is used to view the interior of the human body.

Cambridge University- Atlantic Margins Project

The Atlantic Margins Project (AMP) is investigating the deep structure of the Faroe-Shetland, Rockall-Hatton and Porcupine troughs and surrounding regions using deep seismic reflection and refraction profiling, integrated with potential field studies. The research provides constraints on the thickness and nature of basement, depth to Moho, and the distribution and thickness of basaltic lavas and underplated igneous rock, on a regional scale. A primary scientific objective is to test the theory that magmatic underplating is directly responsible for the early Tertiary epeirogenic uplift observed on the continental shelf of the eastern North Atlantic. The data will also provide new constraints for basin modelling and analysis.

The AMP acquired three deep seismic reflection/refraction lines over the Shetland Platform and Faroe-Shetland Trough, and the airgun shots along these were recorded on four BGS seismograph stations on the Shetland Islands. The landstations recorded clear refracted arrivals from the crust and upper mantle. Over 11,000 first arrival travel-times were picked from the data and input to a 3-D tomographic P-wave velocity inversion code (FAST - First Arrival Seismic Tomography, Zelt and Barton (1998)). Although the spatial distribution of sources and receivers was sub-optimal, the resulting velocity model shows variations in the Moho depth under the platform and trough and also includes basin structures that were not previously resolved by the 2-D AMP models as they lay off-line. Provided that the marine data are acquired with a sufficiently large, low frequency source, timed to an accuracy of 1 ms,
recording the shots on nearby landstations provides an extremely useful, low cost additional dataset.

The AMP research team comprises Richard Hobbs, Rose Edwards and Frauke Klingelhoefer at the University of Cambridge and Richard England at the University of Leicester. Further details and data examples can be found on the project's web-site, at http://bullard.esc.cam.ac.uk/~amp.

ARUP, Imperial College, BGS- Attenuation laws for Nuclear Sites in the UK

British Energy Generation Ltd has commissioned Arup, together with specialists from Imperial College and the British Geological Survey (BGS) to carry out a reassessment and possible revision of the Principia Mechanica Ltd (PML) attenuation relationships derived between 1982 and 1988 for use in the UK nuclear industry. Since these equations were derived, there have been many important developments in strong-motion seismology that have implications for the estimation of seismic hazard in regions such as the UK. These developments include a huge expansion of the global strong-motion database and particularly the recording of an appreciable number of accelerograms from earthquakes in stable continental regions, including the UK. Important advances have also been made with regard to the nature of strong-motion scaling and attenuation in terms of the influence of different independent parameters and the nature of the associated uncertainty.

Phase 1 of the study carried out a critical review of the PML relationships, with reference to developments in strong motion seismology over the last fifteen to twenty years. The data sets on which the PML equations were based have been reviewed and it has been found that only a very small proportion of the records were from stable continental regions such as the UK. Furthermore, several of the values of PGA have been revised by subsequent data processing work and many of the values of magnitude and distance used have also been changed by later studies. The addition of excluded records, the updating of both predictor and explanatory variables, and the use of alternative functional forms have all been shown to produce different equations for PGA. The state-of-the-practice has also developed considerably in terms of site characterisation and the explicit analysis of soil effects on earthquake motions, since the PML (1988) relationships were developed. These effects have been shown to have a significant effect on both PGA and spectral ordinates, potentially unconservative for shallow stiff sites and conservative for soft soil sites.

In phase 2 of the project, new attenuation relationships will be developed using the latest available techniques and data. The work can be broadly split into collation of new and revised data, comparison of stable continental region (SCR) data to UK data, and determination of new UK attenuation relationships. The SCRs for which data is available are north west Europe, Australia, eastern north America, the UK, India and China.

Durham University

A study by Martin and Jackie Bott has been investigating a possible driver for UK earthquakes through Cenozoic uplift in response to anomalous mantle.

A belt of hot, low-density uppermost mantle underlying mainland Britain, revealed by seismic tomography, may be the prime cause of the Cenozoic uplift. We use finite element modelling to demonstrate how isostatic uplift can occur in response to such a low-density region. To explain the narrow width of the uplift, the lower crust must be ductile (power-law rheology assumed) and the asymmetrical uplift must be bounded at least on the west side by a pre-existing fault or faults of appropriate polarity. Faulting can be normal under regional tension as in the Palaeocene, or reverse under regional compression subsequently. With the assistance of ongoing erosion, the inferred gross Cenozoic uplift of up to 2.5 km or more can be explained.

British earthquakes concentrate along a similar north-south belt, with the strongest events in the west. We suggest that the earthquakes result from the ongoing tectonics associated with anomalous upper mantle, its uplift, and the weakened crust. The underlying low-density region gives rise to tensional loading stress in all directions and bending stresses are associated with the upper crustal flexuring accompanying uplift. These quite large stresses supplement NW-SE regional compression. Available earthquake mechanisms are approximately consistent with this stress environment. In such a stress regime, strike-slip events might be expected to predominate, but existing planes of weakness would allow NW-SE thrust events and NE-SW tensional events to occur. If the hypothesis is correct, then the zone of relatively strong mainland seismicity may map the underlying anomalously hot zone more accurately than the tomography that initially indicated its presence.

European and worldwide

For a number of years data exchange with neighbouring countries has been fostered and improved through an EU project led by BGS. This has led to more rapid information becoming available on larger transfrontier earthquakes and harmonisation of the catalogues of data used for hazard assessments. The strong Ekofisk earthquake of 7 May 2001 resulted in the pooling of data from some eight countries to better understand its mechanism, depth and cause. Determination of a robust focal mechanism for the 22 September 2002 Dudley earthquake (4.7 ML) was achieved through wide collaboration across Europe utilising broadband stations. Under another EU project for disseminating rapid warnings on earthquakes with magnitudes ≥ 5.0, parts of the UK network have been linked automatically to the European Mediterranean Seismological Centre at Bruyeres-le-Chatel, south of Paris. Separately, French workers have been provided with data on English Channel earthquakes to constrain focal mechanisms.

Data recorded on the UK network is routinely supplied to European and global data integration centres (EMSC, ORFEUS, ISC and USGS) from where it is made openly available to researchers, engineers and hazard assessment specialists.

SYNOPSIS OF EMS-98 INTENSITY SCALE

1 - **Not felt**
Not felt, even under the most favourable circumstances.

2 - **Scarcely felt**
Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.

3 - **Weak**
The vibration is weak and is felt indoors by a few people. People at rest feel a swaying or light trembling.

4 - **Largely observed**
The earthquake is felt indoors by many people, outdoors by very few. A few people are awakened. The level of vibration is not frightening. Windows, doors and dishes rattle. Hanging objects swing.

5 - **Strong**
The earthquake is felt indoors by most, outdoors by few. Many sleeping people awake. A few run outdoors. Buildings tremble throughout. Hanging objects swing considerably. China and glasses clatter together. The vibration is strong. Top heavy objects topple over. Doors and windows swing open or shut.

6 - **Slightly damaging**
Felt by most indoors and by many outdoors. Many people in buildings are frightened and run outdoors. Small objects fall. Slight damage to many ordinary buildings eg; fine cracks in plaster and small pieces of plaster fall.

7 - **Damaging**
Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many ordinary buildings suffer moderate damage: small cracks in walls; partial collapse of chimneys.

8 - **Heavily damaging**
Furniture may be overturned. Many ordinary buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse.

9 - **Destructive**
Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely.

10 - **Very destructive**
Many ordinary buildings collapse.

11 - **Devastating**
Most ordinary buildings collapse.

12 - **Completely devastating**
Practically all structures above and below ground are heavily damaged or destroyed.

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A complete description of the EMS-98 scale is given in: Grunthal, G., (Ed) 1998. European Macroseismic scale 1998. Cahiers du Centre European de Geodynamique et de Seismologie. Vol 15.

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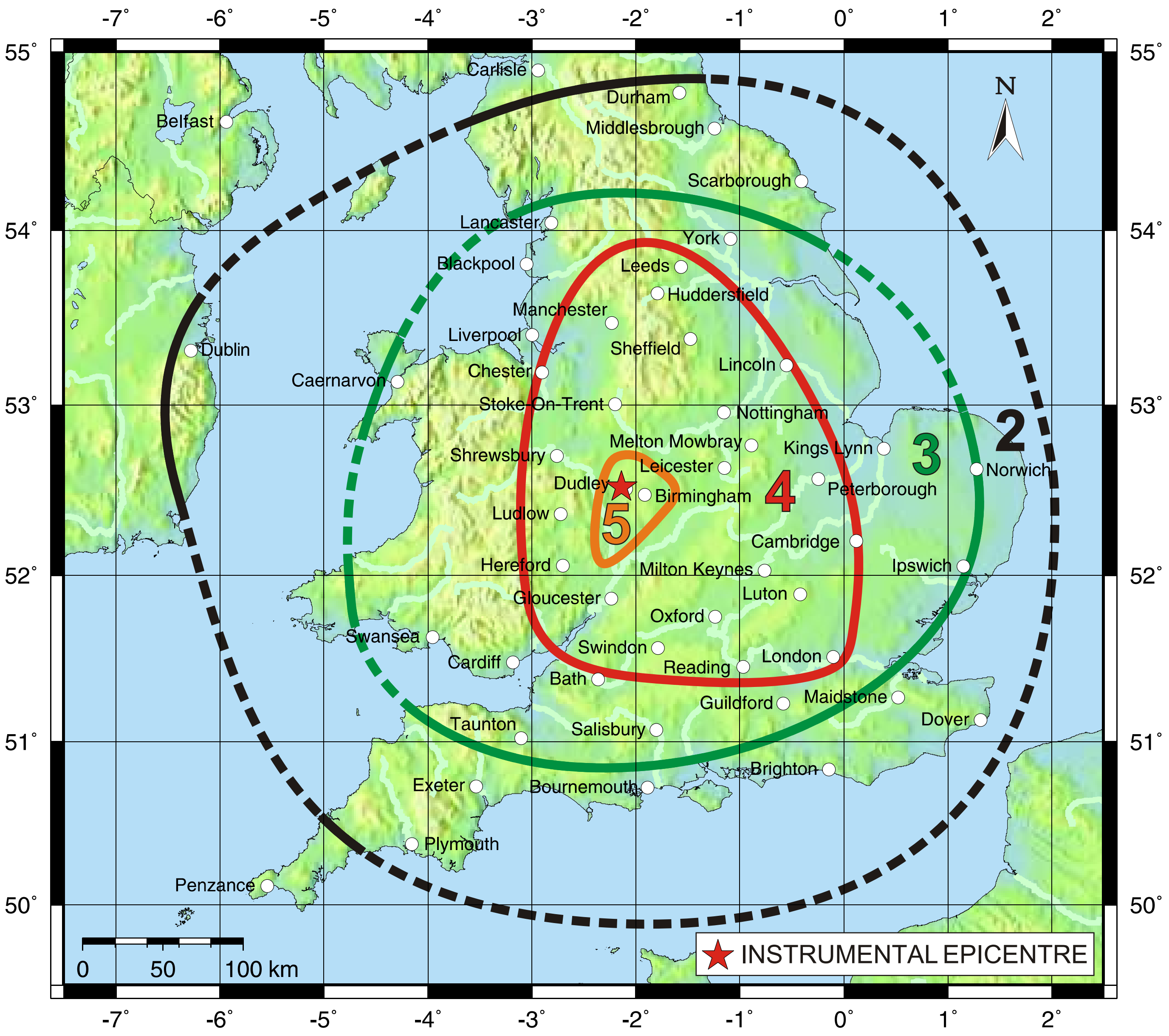

Dudley Earthquake 22 September 2002 23:53 UTC (4.7 ML) - EMS Intensities