# UK EARTHQUAKE MONITORING 2000/2001

# BGS Seismic Monitoring and Information Service

## Twelfth Annual Report

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**BRITISH GEOLOGICAL SURVEY**

**TECHNICAL REPORT IR/01/46**

**Global Seismology and Geomagnetism**

# UK Earthquake Monitoring 2000/2001

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## Twelfth Annual Report

**Alice B Walker**

**June 2001**

**UK Seismic Monitoring and Information Service Year Twelve Report to Customer Group: June 2001**

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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

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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.

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# UK EARTHQUAKE MONITORING 2000/2001

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

In the 12th year of the project (April 2000 to March 2001), four networks were upgraded with the installation of QNX operating systems. 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 156 UK earthquakes were located by the monitoring network in 2000, with 35 of them having magnitudes of 2.0 ML or greater and 17 reported as felt. Six strong-motion records were captured from five of the eighteen sites now equipped with strong motion instruments. The largest felt earthquake in the reporting year, with a magnitude of 4.2 ML, occurred near Warwick on 23 September. A macroseismic survey was conducted and around 2,500 replies were received, giving a maximum intensity of 5 EMS (European Macroseismic Scale, Annex H). It was felt up to 150 km away and over an area of 14,900 km$^2$ (Isoseismal 3). The nearest 3-component strong motion instrument to record the earthquake was 76 km from the epicentre and accelerations of 17.2, 16.6 and 20.8 mms$^{-2}$ were recorded for the vertical, NS and EW components, respectively. The focal mechanism indicates almost pure normal faulting on a NW-SE oriented plane, dipping either to the NE or to the SW. The largest offshore earthquake occurred in the northern North Sea on 8 December. It had a magnitude of 4.6 ML and was located approximately 175 km east of the Shetland Islands. It was felt on a nearby oil platform in the Bruce field, 20 km south west of the epicentre. 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 on one controlled explosion and 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 fax and were subsequently followed up in more detail. The alerts were also available on the Internet (www.gsrg.nmh.ac.uk). Monthly seismic bulletins were issued 6 weeks in arrears and, following revision, were compiled into an annual bulletin (Simpson, 2001). In all these reporting areas, scheduled targets have been met or surpassed.

The environmental monitoring station at Eskdalemuir Observatory has been recording 20 parameters throughout the year and is 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 formally started in April 1989 and the Year 1 report includes details of the history of seismic monitoring by BGS since 1969, as well as the background to the establishment of the project. Earthquake monitoring information 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. This work helps 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 to be able to give objective information as soon as possible after significant ones in order to allay any unnecessary worries. 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.

This Year 12 report to the Customer Group follows the format of the first eleven annual reports in reiterating the programme objectives and highlighting some of the significant seismic events in the reporting period, April 2000 to March 2001. The catalogue of earthquakes for the whole of 2000 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 magnitude ≥2.5 ML; the threshold above which the data set is probably complete. Such events are normally felt by people.

To improve the capacity of the network to deliver on-scale data for the larger earthquakes, and to more effectively calculate their magnitudes, strong motion instruments have been added to it. They record ground acceleration for the larger felt earthquakes, remaining on-scale up to 0.1g. There are eighteen strong motion stations in the UK. Traditionally, strong motion and high sensitivity networks have been treated separately for technical reasons but the digital technology now employed permits both to be integrated with benefits in cost and reliability. Most importantly, this approach ensures there is a pool of analysts familiar with extracting and processing data despite the infrequency of strong motion earthquakes. Now that 24-bit technology can capture data with accelerations up to 0.25g, the strong motion instruments are being upgraded as funds permit.

The six temporary broadband stations installed throughout the country in collaboration with Leeds and Bristol Universities, were removed in September 2000. The principal focus of the deployment was to investigate discontinuities and scattering in the Earth's mantle by analysis of teleseismic waveforms from the South Pacific region (more details in section 3.2.1). The permanent BGS broadband station in Edinburgh has been upgraded to 24-bits and is continuing to provide data through a French satellite system to the European-Mediterranean Seismological Centre (EMSC). 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 with magnitudes greater than 5.0.

Filling the few remaining gaps in the high sensitivity network, which is intended to have effective station spacing of 70 km, continues to be a project objective although no progress has been possible during the year.

All of the advances made and proposed in the effective background network of the UK can be seen by comparing the present coverage (Fig. 1) with that in 1988 (Fig. 2), although some reliance remains on data contributed from separately funded, site-specific networks in Jersey, northern Scotland, Outer Hebrides and the Orkney Islands. These are vulnerable to closure when the commissioning organisations have completed the work for which they were installed. For the next twelve months, however, there is no threat. The developing strong motion coverage is shown in Figure 6.

## 3. Programme objectives

The overall objectives of the service established in 1988 were:

- To provide a database for seismic risk assessment using existing information together with that obtained from a uniform distribution of modern seismograph stations throughout the UK landmass. A mobile network of seismograph stations would be used for specific investigations of seismic events to supplement the background network.

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

- To establish and maintain a database and archive of seismicity and seismic records.

These objectives and a strategy to meet them were described more fully in a proposal from BGS dated December 1987. The higher the density of seismograph stations in the network, the more accurate will be the response and the database. In discussion with the Customer Group, a 70 km average spacing of stations (Fig. 5) was agreed as a cost-effective way of achieving the main goals although it was recognised that the determination of some parameters (eg depths of focus and focal mechanisms) could only be approximate. Advantage was taken of existing site-specific monitoring networks so that, in places, the overall network density is greater than 70 km spacing.

As the programme developed under the guidance of the Customer Group, further objectives were added:

- To develop a strong motion capability within the network to permit the maximum ground accelerations to be captured on-scale from nearby small earthquakes and widely from the rare larger ones.

- To guarantee a 24-hour on-call service by experienced seismic analysts.

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

- To extend the environmental parameters monitored in order to broaden customer support.

### 3.1 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.

- The installation of seismograph stations to fill in the gaps for the 70 km spacing objective; from 84 stations in 1988 to 146 in 2001. Large areas have been filled in to give coverage of southern England, the Irish Sea, northern Scotland and, recently, in the Faroe islands to cover offshore northern Scotland.

- The detection capabilities of the network have gradually improved with increasing station coverage, and Figures 3 and 4 illustrate the change over the 13-year project period. Almost all magnitude 2.5 earthquakes are felt together with many in the 2.0-2.5 range, but, in 1988, there was poor coverage of such events in many parts of the country.

- In 1988, all stations were recording onto magnetic tapes, which were posted to Edinburgh for analysis. Access to data was generally achieved within two working days of a felt earthquake. Since 1997, stations record digitally with data transferred automatically four times a day and on demand when an earthquake occurs. Response time with objective data has been reduced to below one hour, which can generally be achieved outside working hours also.

- All UK station positions have been resurveyed using GPS techniques.

- Faster modem links have been installed at all computer recording nodes (24 in total).

- Following upgrading of digital rapid access systems, the potential problem of losing a continuous data record has been addressed by installing large capacity disks, allowing up lring buffer.

- In order to improve the study of seismicity in the border regions of the North and Irish Seas and the English Channel and SW Approaches, strong data exchange links have been established with European neighbours and with the international agencies, EMSC, ORFEUS and ISC (the European Mediterranean Seismological Centre, Paris, European broadband Centre, Netherlands, and the International Seismological Centre, Newbury). In the North, collaboration with Bergen University has provided direct access, on-line, to digital seismograph stations in western Norway. Elsewhere, BGS has coordinated a 10-nation data exchange network (the Transfrontier Group) from Denmark to Portugal under the EU natural hazards programme.

- A 3-component strong motion network of eighteen stations has been installed from Shetland to Jersey including four stations specifically commissioned by British Energy, MOD and the Jersey New Waterworks Company.

- A computer bulletin board has been established which provides access to catalogued seismic events for the previous 12 months, their phase data and details of seismic alerts issued. The Global Seismology Web site provides access to data through the Internet to the past month's catalogue of events and to UK and world seismic alerts.

- Historical material from former UK seismic stations has been brought together and housed in a National Seismological Archive (NSA) at the BGS laboratories in Edinburgh, with a computer-index. A watching brief has been kept on other archives, held elsewhere, with a view to increasing knowledge of the content and preventing their dispersal or destruction. Some of those collections have been transferred to Edinburgh as a result of these interactions. A series of eight reports has been made available on-line for downloading.

- 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 held on ½" FM magnetic tapes, have been extracted and digitised for events with magnitudes ≥2.0 since 1977. There remains some potential data on the Edinburgh network for the period 1970-1976, recorded on a 1" tape format, which has proved difficult to extract owing to the condition of the tapes and old replay equipment.

- The instrumental digital 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.

- 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).

- 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. Twenty environmental parameters have been interfaced with the seismic data transmission systems and data files to demonstrate the network's capability to provide baseline information, long term trends, climate change parameters and long-range impact of industrial plumes. A Memorandum of Understanding (MOU) with the Meteorological Office has laid the basis of collaboration and meteorological quality control.

### 3.2 Uses of the seismic database

In addition to the specific needs of the Customer Group members, the seismic database is used by a variety of organisations both in the UK and worldwide. A summary of the use made of this 31-year catalogue and digital archive of earthquakes, during the past year, follows:

### 3.2.1 University collaboration

**Bristol University; Mapping seismic discontinuities**

A new 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 ($10^2$-$10^2$ m) 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 these 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 (Fig. 6), 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.

In the first year of his PhD, 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.

In May 2000, the project collected wide-angle reflection and refraction data along two profiles in the northern Rockall Trough using 50 OBS (Ocean Bottom Seismographs) and a large, low frequency, airgun array. Modelling of the OBS data has provided a cross-section of the crustal structure across the northern Rockall Trough. The airgun shots were also recorded by land seismometers from the British Geological Survey's Minch network, located on the Outer Hebrides and the west coast of mainland Scotland. These data have provided an extremely useful westwards extension to one of the wide-angle lines which was shot in a northwest – southeast direction. The land station data shows clear refracted and reflected arrivals to offsets in excess of 180 km. These data have helped to constrain the structure of the lower crust and upper mantle under the eastern flank of the Rockall Trough.

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.

### 3.2.2 European collaboration

For a number of years, stimulated, through an EU project led by BGS, data exchange with neighbouring countries has been fostered and improved. This has led to more rapid information becoming available on larger transfrontier earthquakes and harmonisation of the catalogues of data used for hazard assessments. 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.

Collaboration with the Faroese Museum of Natural History, has continued and data from the Faroe Islands network has considerably improved the monitoring of seismic events offshore northern and western Scotland. This collaboration has also produced the first ever study of the historical seismicity of the Faroe Islands which demonstrated a low level of activity in the past 400 years.

Major international projects that have drawn upon the UK database include the Global Seismic Hazard Assessment Programme (GSHAP), an International Decade for Natural Disaster Reduction (IDNDR) project from which hazard maps and reports have been published recently. This major international project was one of the key activities of the Decade with BGS involved at all stages of the project and having a particular focus on the British Isles and the North Balkan area. A successor project for the Mediterranean area (SESAME) is also proceeding with BGS assistance.

Joint developments to upgrade data acquisition and analysis software, with Bergen University, have continued.

Collaboration continues with Aristotle University, Thessaloniki, Greece and Edinburgh University on the subjects of time-dependent seismic hazard, earthquake maximum magnitude, and intensity attenuation.

As a result of a resolution passed at the last European Seismological Commission (ESC) General Assembly, a provisional committee has been established to investigate the formation of a European field investigation team for making specifically seismological (as opposed to engineering) surveys of the effects of major European earthquakes; BGS is actively involved in this project.

### 3.2.3 Hazard studies and database enquiries

The BGS database continues to play an important role in studies of UK seismic hazard. There are two principal applications: safety case preparation for hazardous facilities and more general hazard assessments. Advice is also given on seismic hazard for specific sites for a variety of engineering projects. Overseas, significant hazard studies were completed for sites in India and Gibraltar.

BGS uses its own in-house software for seismic hazard calculations, and this has been upgraded during the year to bring in new features, including formal logic tree modelling. Previous versions of the program use a different technique (continuous distributions of parameters) for modelling uncertainty, which is considered to be superior to the logic tree approach. However, having the option to apply logic trees is useful for purposes of comparison with other studies. The program (called M3C) also has options for easy calculation of hazard as effective peak acceleration or uniform risk spectra.

A topic of interest in hazard studies at present is the formal validation of seismic hazard models, which represents a new way of evaluating the reasonableness of results. An invited paper on the subject was given to a workshop meeting on seismic hazard mapping in Slovenia in May 2000 (Musson, 2000 – Annex G).

**Reinsurance**

The program developed by BGS in conjunction with Hiscox Syndicates for assessing earthquake risk to reinsurance portfolios is now complete in its second version, with facilities to handle reinstatements and deductables and other new features. Marketing of the new version has been put on hold for the moment while the strategic positioning of the project is considered. There exist options for widening the product scope which are currently under discussion with prospective partners.

**Strong motion records**

With the expansion of the strong motion network in the past few years, strong ground accelerations, which would previously have saturated the network, are being recorded from British earthquakes. To-date, twenty-two three-component strong motion records (Table 1) have been recorded for earthquakes with magnitudes between 1.1 and 4.2 ML at distances of between 3 and 166 km. Six of these records were written in the reporting year. The values of acceleration measured from these instruments are less than those expected from the attenuation laws currently used for the UK (PML, 1988; Ambraseys and Bommer, 1995; Dahle et al. 1990). However, most of these relations are not appropriate for small magnitude earthquakes. Attenuation of small events tends to be higher than for larger events because they have a higher frequency content, and higher frequencies attenuate faster. Of necessity, these laws have been constructed using empirical data from more seismically active regions using earthquakes with larger magnitudes. The build-up of UK records by BGS will eventually permit more appropriate relationships to be established for use by engineers in this country.

**Broadband Seismometry**

Broadband seismometers record ground motion over a wider frequency range than conventional short period instruments. Such instruments are typically used for analysis of large earthquakes at teleseismic distances, which generate and propagate the longer period waves. 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 our understanding of crustal structure in the locality of the recording instrument. This leads 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 has been upgraded to provide high dynamic range, 24-bit continuous data. The next stage is to provide near real-time data on the BGS web pages and also make the data available from our AutoDRM (Automatic Data Request

Manager). Data from a broadband sensor at the Eskdalemuir seismic array, that uses the same acquisition hardware, will also be available in this way. Broadband data are also readily available from the United States IRIS station hosted by BGS at Eskdalemuir Observatory.

The temporary array of broadband sensors installed by Leeds and Bristol Universities recorded data continuously at 6 sites across the UK from July 1998 to September 2000. Although the main purpose of the deployment was to record teleseismic earthquakes for investigating discontinuities deep within the earth's mantle, BGS has been able to utilise the information for studying local earthquakes and crustal structure.

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

Some 860 enquiries have been answered during the year, with intense interest following felt UK events and the devastating world earthquakes in El Salvador and India. Some 22 TV and 39 radio interviews were conducted. Of these 8 TV interviews and 14 radio interviews were prompted by UK earthquakes.

**Data exchange and world reporting**

BGS data is exchanged regularly with European and world agencies to help locate and improve focal mechanism parameters for earthquakes outside the UK. As a *quid pro quo*, BGS receives data on UK earthquakes and world events of relevance to the UK, recorded by many other agencies and institutions.

**Test ban treaty verification**

Data has 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.

**Earthquake statistics**

The UK instrumental database is 30 years long, although completeness in the early years, to 1978, is probably only at magnitudes of 3.5 and greater. Since 1979, the completeness threshold is magnitude 2.5. The total statistics for earthquakes of magnitudes ≥ 2.0, shown in Figure 23, 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 24 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 although the increase in 1996 can be attributed to the Monktonhall series near Edinburgh and the miners strikes between 1983 and 1985 explains the low level at that time. For the natural earthquakes, peaks can be attributed to swarm activity in 1974 (Kintail), 1980 (Carlisle), 1981 and 1986 (Constantine) and in 1984 (North Wales). The seismogenic thickness of the earth's crust across the UK is demonstrated by the distribution of earthquakes with depth. The higher quality data available to date indicates significant geographic variations; for example, the majority of earthquakes in Scotland are relatively shallow (< 15 km), whereas in Wales, earthquakes occur at greater depths (10-25 km). Most earthquakes in Cornwall are shallow (<7 km) probably due to high heat flow associated with granite intrusions. Shallow coalfield events (< 2km) dominate the Midlands region and the eastern end of the Midland Valley of Scotland, but these are probably induced by mining.

**Focal mechanisms**

Earthquake focal mechanisms are a basic tool used in the investigation of both local and regional tectonics, providing information on the style of faulting that is occurring in the crust. In the past, focal mechanisms could only be obtained for the largest events. As a result of the expansion of the UK network over the years, an increasing number can be determined for smaller events, which are now recorded on many stations. In areas of North Wales, Cumbria, the Scottish Borders and Cornwall, events with magnitudes of less than 2.0 ML can be processed in this way.

Three focal mechanisms were obtained during the reporting period; for earthquakes at Calthwaite (ML 2.6), Lleyn Peninsula (ML 2.7) and Warwick (ML 4.2). The mechanisms obtained for Calthwaite and Warwick show predominantly normal faulting along fault planes striking approximately NNW-SSE and NW-SE respectively. The Lleyn Peninsula mechanism, although less well constrained, shows elements of both strike-slip and oblique normal faulting.

In collaboration with the Nuclear Installations Inspectorate (NII), a systematic program of revising the focal mechanism catalogue is underway. As more focal mechanisms are obtained, we gain a better understanding of the stresses that cause earthquakes in the UK. The results are being compiled in a GIS database showing 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. However, initial examination suggests that the orientation of the minimum compressive stress direction appears remarkably consistent, striking approximately NE-SW, and in keeping with the regional tectonic setting.

**Public Understanding of Science**

A number of lectures and presentations have been given to school and university students and other interested parties. Over 200 media interviews have been conducted, including 22 for TV broadcasts and 41 for radio, (Fig. 25) following significant earthquakes. The BGS was featured in a BBC programme on the pop group Madness which, in 1992, caused alarm around Finsbury Park, London, when their concert generated earthquake-like ground vibrations which were felt up to 1 km away. The Internet home page has been a source of information for both the public, media and other organisations, with over 172,000 visits in the year. BGS, in collaboration with UKAEA, produced an updated booklet, which included damage pictures of the recent El Salvador and India earthquakes and some earthquake statistics. This was distributed to the Customer Group in early March and is being used in school educational packs, at workshops for schools, at various science festival events throughout the country and for general enquiries.

# 4. Development of the monitoring network

## 4.1 Station distribution

The network developed to March 2001, with rapid-access upgrades, is shown in Figure 1 with its detection capability in Figure 3. The scheduled programme for 2000/2001 had as its aims:

(i) Further installations of the QNX operating system.

(ii) Installation of additional 4 gigabyte disks to increase the continuous recording capability at sites where such capacity can be utilised.

(iii) Introduction of new strong motion systems at sub-network digital acquisition centres, priority being Swansea.

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

(v) Collaboration with Universities to secure further broadband data.

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

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

Four QNX systems have been installed in Leeds, south east England, Hereford and Kyle (i). The programme of installation of 4 Gb disks (ii) has been superseded by the installation of QNX systems which provide up to 60 Gb of storage and a continuous recording buffer of up to 100 days. The introduction of a new strong motion system (iii) near Swansea was delayed owing to the foot and mouth outbreak. A new strategy is being adopted in the next year to upgrade, where possible, the 3-component stations (high gain and strong motion) to 24-bit, thereby allowing both small and large earthquakes to remain on-scale. The distinction between high sensitivity and strong motion instruments will gradually disappear through this process and a much improved strong motion capability will result. During the year, a further six strong motion records have been obtained from the following earthquakes; Calthwaite, Lleyn Peninsula, Middlesborough and Warwick earthquakes (Table 1). (iv). Collaboration with the Universities of Bristol and Leeds has been maintained and work has started with the University of Carolina on the temporary installation of broadband instruments in Scotland (v). Contact with archives outside BGS has been maintained (vi). Data has been supplied to IASPEI and work is progressing with the international effort to make archives available electronically (vii).

## 4.2 Strong motion network

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. The "importation" of such records from plate margin zones, however, may detract from the realism of analyses conducted in intraplate areas such as the UK. In recognition of the importance of measured strong ground motions, therefore, the project has focused on developing a distribution of 3-component instruments, which would remain on-scale for the larger British earthquakes when the high sensitivity network saturates.

The present distribution of strong motion instruments together with the temporary broadband (removed in September 2000) and low-gain instruments, microphones and the environmental stations, is shown in Figure 6. Fifteen of the 18 strong motion stations generate open-file data; the other three are operated by, or on behalf of, British Energy and MOD. Strong motion records have been written for the following earthquakes this year; the Calthwaite, Lleyn Peninsula, Middlesborough and Warwick earthquakes.

The impact of this growing network can be seen in Figures 7-10, which show the minimum and maximum magnitudes of earthquakes which can be detected and stay on-scale, as contour maps. Comparisons are drawn between the early phase of development (Figs. 7 and 8) and that prevailing at present (Figs. 9 and 10). Over most of Britain, a magnitude 4.0 earthquake will produce an on-scale trace on at least one strong motion instrument and only rarely will a magnitude 6.0 event cause saturation at any station. The largest known earthquake in the several hundred year historical record, occurred near the Dogger Bank in 1931 with an estimated magnitude of 6.1 ML. As noted in 4.1, the anticipated upgrade of the network to 24-bits will extend the strong motion capability further and increase the rate of capture of strong ground motion records.

### 4.3 Related site specific monitoring

With regard to the continuation of site-specific monitoring projects on which the present network depends:

(i) The Jersey New Waterworks Company has continued to support the monitoring network on Jersey.

(ii) The free-field strong motion system for British Energy at Torness has continued to operate and a proposal to upgrade the Hunterston equipment has been submitted.

(iii) The 13 stations in northern Scotland and the Orkney Islands, supported by an oil company consortium and the Health and Safety Executive (HSE), has continued with funding assured until March 2002.

In summary, coverage of the country is almost complete with the aid of these site-specific networks. In the longer-term, however, they represent areas of vulnerability owing to the prospect of the withdrawal of funding.

### 4.4 Progress with instrumentation

The new data acquisition equipment, using the QNX operating system, is now installed at eight locations with four added in the last year. The upgrades are at Edinburgh, Eskdalemuir

(Scottish Borders), Faroe Islands, the Orkney network, Leeds, Hereford, south east England (Kent), and Kyle. QNX gives a number of advantages over the SEISLOG systems; increased processing power, larger memory capacity (from 8 Gb to upwards of 60 Gb), improved communication links using Ethernet cards and ISDN links (digital telephone lines), together with greater portability. The systems already installed give up to 14 days ring buffer and throughout the coming year new, larger capacity disks will be installed to allow up to 100 days ring buffer. These large capacity disks help prevent potential losses if the event-triggered systems miss spurious events, very small earthquakes and sonic booms.

In addition to the QNX systems, there are now 8 networks with 4Gb disk storage (providing up to 10 days ring buffer) and 7 with one gigabyte disk storage, which provides a three-day window of continuous data.

### 4.5 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 allows 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 this network and be sampled every minute.

Currently, there are five environmental stations in operation in southern Scotland. Three on the outskirts of Edinburgh at Loanhead, Stoneypath and Dunslair (the latter is operated in collaboration with the NERC Centre for Ecology and Hydrology (CEH)), and two in Eskdalemuir, at the Observatory and at the Seismological Array Station (EKA). The concept was developed with limited sensors at the first three sites and a full demonstration system installed at Eskdalemuir during 1999. This network was extended during 2000 to include a remote radio linked meteorological monitoring site at EKA. Sensors deployed in the Eskdalemuir sites monitor the following pollution and meteorological parameters: ozone, sulphur dioxide, nitrogen oxides, wind speed and direction, air temperature, soil temperature, rainfall, humidity, surface wetness, Ultra violet (UVB) and nuclear radiation and sunshine. The data at Eskdalemuir are recorded using a Campbell Scientific logger and a BGS designed logger, both of which are interfaced to a networked computer. The Eskdalemuir site has the advantage of being a Meteorological Office site and direct comparisons between the Meteorological Office data and the BGS recorded data can be made. The ITE site at Dunslair has an ozone sensor, the data from it is digitised on site and radio linked back to Edinburgh where it is recorded. Loanhead has sensors monitoring temperature and humidity, which are transmitted directly to the Edinburgh recording site. Stoneypath, the original test site installed by BGS, monitors UVB, air temperature, ground temperature, humidity and nuclear radiation. Data from all these outstations can either be made available to users by e-mail or viewed on-line using WWW browser software.

Potential users of the system, including the Scottish Environmental Protection Agency (SEPA), Environment Agency (EA) and the Scottish Water Authorities, have been kept informed of the monitoring capabilities with a view to seeking further support for its development. A Memorandum of Understanding with the Meteorological Office is designed to explore possible avenues of collaboration.

# 5. Seismic activity in Year 12

## 5.1 Earthquakes located for 2000

Details of all earthquakes, felt explosions and sonic booms detected by the network have been published in monthly bulletins and, with final revision, are provided in the BGS bulletin for 2000 published and distributed in April 2001 (Simpson, 2001). A map of the 156 events located in 2000 is reproduced here as Figure 11 and a catalogue of the 35 with magnitudes of 2.0 or greater is given in Annex B. Eight events in that magnitude category, together with 9 smaller ones, are known to have been felt.

Spatially, the distribution of seismicity in 2000 was similar to that of 1999 and 1998 with the majority of earthquakes occurring in and around Wales, the Midlands, Cumbria, the Borders, and in central and western Scotland. Some activity occurred around the Channel Islands and in the northern North Sea. There were no events in Ireland and north east Scotland, both of which experienced earthquakes in 1999. Some earthquakes were located in regions that have previously experienced few instrumentally located ones; for example, off the Norfolk coast, Warwick, Middlesbrough, and around the Shetland Islands. The south east of England continued to be aseismic in 2000, along with Ireland, northern Scotland, central and eastern Scotland, and the Outer Hebrides. Historically, south east England has been active but Ireland, northern Scotland, and central and eastern Scotland have experienced few events in the past. Earthquake occurrence during 2000 was fairly uniform throughout the year, except for a period of relative quiescence during October and November, followed by increased activity in late December. Periods of relative quiescence are not uncommon in the earthquake record and reflect the natural variation in the rate of earthquake occurrence. A few locations experienced several events during the year, the most active region being around Blackford, Tayside, with 14 events during 2000, 7 of which occurred between 17 and 28 December. Other clusters (of 5 or more events) occurred near Dumfries, Caernarvon Bay, Lleyn Peninsula and Torridon. The largest event in 2000 was the Warwick earthquake, with a magnitude of 4.2 ML.

In the period since BGS extended its modern seismic monitoring in the UK (1979 to March 2001), almost all of the earthquakes with magnitudes ≥2.5 ML are believed to have been detected. The distribution of such events for that period (Fig. 12) is, therefore, largely unbiased by the distribution of seismic monitoring stations for the onshore region. Accuracy of individual locations, however, will vary across the country and with time.

## 5.2 Significant events

Highlights of the seismic activity during the twelfth year of this collaborative project (April 2000 to March 2001) are given below:

(i) An event near Calthwaite, Cumbria with a magnitude of 2.6 ML occurred on 24 April and felt reports described "the whole house shook" and "the windows rattled", indicating an intensity of at least 3 EMS. A seismogram of the earthquake recorded on the Borders network is shown in Figure 13. A focal mechanism for the larger event was calculated and shows dominantly normal faulting with a minor component of strike-slip. The nodal planes strike NNW-SSE. The nearest 3-component strong motion instrument to record the earthquake was 38 km distant and accelerations of 1.3, 7.1 and 1.4 $mms^{-2}$ were recorded for the vertical, NS and EW components, respectively.

(ii) On the Lleyn Peninsula, North Wales, an earthquake, with a magnitude of 2.7 ML, was felt by local residents in Dinorwic, Maentwrog, Llanberis and Caernarvon on 22 June. The reports described "the whole house shook" and "felt a shudder", indicating an intensity of at least 4 EMS. A further 5 events with magnitudes ranging between 0.0 to 0.7 ML, were also located 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. A seismogram of the event recorded on the North Wales network is shown in Figure 14. The nearest 3-component strong motion instrument to record the earthquake was 47 km distant and accelerations of 1.7, 2.1 and 3.2 $mms^{-2}$ were recorded for the vertical, NS and EW components, respectively. The calculated focal mechanism shows dominantly strike-slip faulting with a varying component of dip-slip. The nodal planes strike WNW-ESE and N-S. This is in reasonable agreement with the calculated focal mechanism for the 1984 earthquake. The P and T-axes (compressional and tensional) are consistent with the regional stress direction for the UK. This is the largest event in the Lleyn Peninsula area since the magnitude 2.7 ML earthquake on 15 April 1986, which was felt with intensities of at least 2 EMS in Pwllheli and Porthmadog.

(iii) Near Middlesbrough, Cleveland, an earthquake with a magnitude of 2.7 ML occurred on 8 August. Earthquakes of this size are usually felt when they occur onshore but enquiries to local police stations and post offices revealed that no felt reports were received. The depth (24.4 km) may have contributed to the lack of felt effects. The nearest 3-component strong motion instrument to record the earthquake was 124 km distant and accelerations of 0.3, 0.2 and 0.3 $mms^{-2}$ were recorded for the vertical, NS and EW components, respectively. This is an area that has experienced little seismicity in both the historical and instrumental periods, with only two events located since 1970 within 10 km of this one.

(iv) Four earthquakes occurred near Arran, with magnitudes of between 0.9 and 2.2 ML. The largest was located with a similar epicentre and depth as the magnitude 4.0 earthquake in March 1999, which was felt over an area of 18,700 $km^2$ (isoseismal 3) and intensities up to 5 EMS.

(v) The largest onshore earthquake in the year, with a magnitude of 4.2 ML, occurred near Warwick on 23 September. It was felt up to 150 km away and over an area of 14,900 $km^2$ at isoseismal 3 EMS. A macroseismic survey conducted after the event yielded over 2,500 replies and the resulting map of felt effects is shown in Figure 26. The highest observed intensity was 5 EMS at Warwick, where, in a number of cases, objects such as ornaments, pictures or toys fell or were displaced. In a few cases, heavy objects were also said to have been displaced, including two washing machines, a cooker, a microwave and a sofa. A seismogram of the event recorded on the North Wales network is shown in Figure 15. The nearest 3-component strong motion instrument to record the earthquake was 76 km distant and accelerations of 17.2, 16.6 and 20.8 $mms^{-2}$ were recorded for the vertical, NS and EW components, respectively (Fig. 16). The focal mechanism indicates almost pure normal faulting on a NW-SE oriented plane, dipping either to the NE or to the SW.

(vi) Near Dollar, an earthquake with a magnitude of 1.1 ML, occurred on 25 September. Felt reports were received from the village of Rumbling Bridge, where intensities reached at least 2 EMS. Felt reports described "a rumbling beneath the feet", "felt a thud" and "the whole house shook". This is the first felt event in the Dollar area, since the magnitude 1.0 ML earthquake, on 25 August 1999, which was felt in the Forest Mill area, with intensities of at least 2 EMS.

(vii) An earthquake, with a magnitude of 1.4 ML, occurred near Mold, Clwyd on 3 November. Felt reports were received via the North Wales Environment Agency, Flintshire County Council and residents of Eryrys and Nercwys. Felt reports described "heard a tremendous bang", "like a boulder hitting the side of the house" and "ornamental plates on the shelves rattled", indicating an intensity of at least 4 EMS. This is the first felt event within 30 km of Mold, since the magnitude 4.5 ML Widnes earthquake, on 3 November 1976, which was felt with intensities of 4 EMS.

(viii) The largest offshore earthquake occurred in the northern North Sea on 8 December. It had a magnitude of 4.6 ML and was located approximately 175 km east of the Shetland Islands. It was felt on a nearby oil platform in the Bruce field (20 km SW of the epicentre). One staff member reported that "the size of the movement was similar to that experienced in storm conditions although the sea state wasn't more than a few metres at the time". Using a standard attenuation formula, it is estimated that a ground acceleration of 0.04g might have been experienced at this range; enough to be felt strongly on land. Platform dynamics may have amplified the effect at deck level.

(ix) Near Swindon, Wiltshire, an earthquake, with a magnitude of 2.7 ML occurred on 18 March. Earthquakes of this size are usually felt when they occur onshore but enquiries to local police stations in the area, revealed that no felt reports were received. A seismogram of the event recorded on the Hereford network is shown in Figure 17.

(x) Four events, with magnitudes ranging between 0.7 and 1.2 ML, occurred near Dumfries, Dumfries and Galloway. The largest, on 17 July, was felt by local residents in the Tinwald area, where intensities reached at least 3 EMS.

(xi) Eleven earthquakes were detected in the Blackford area of Tayside during the reporting year, with magnitudes ranging between 0.4 and 2.1 ML. The largest occurred on 9 August and was felt in the Blackford and Glendevon areas of Tayside, where intensities reached at least 4 EMS. Felt reports described "the furniture moved" and "the building shook". 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 and 3 in 1999. In the same general area on 19 February 1979, a magnitude 3.2 ML Ochil Hills earthquake was felt with a maximum intensity of 5 EMS.

(xii) The coalfield areas of Northumberland, Nottinghamshire, Yorkshire and Staffordshire continued to experience earthquake activity of a shallow nature which is believed to be mining induced. Some 11 coalfield events, with magnitudes ranging between 0.8 and 1.9 ML, were detected in the year. Three of these were reported felt by local residents.

(xiii) Near Rotherham, South Yorkshire 2 events with magnitudes of 1.4 and 1.5 ML were detected; the magnitude 1.4 ML event occurred on 26 June and was felt in the Spotswood area of Rotherham with intensities of 3 EMS. Felt reports described "the windows rattled and the house shook".

(xiv) Near Doncaster, South Yorkshire, two events with magnitudes of 1.7 and 1.9 ML, occurred; both events were reported felt in the Doncaster area. Felt reports for the latter were received via Yorkshire Television and from residents of the Woodlands area of Doncaster, where intensities reached at least 5 EMS. Felt reports described "the walls shook" and "the whole street ran outside". A seismogram is shown in Figure 18. This is an area that has experienced similar events in the past.

(xv) In other coalfield areas, small events were located near Haltwhistle, Northumberland (1.1 ML, 10 April 2000), Ollerton, Nottinghamshire (1.1 ML, 11 April 2000), Market Worsop, Nottinghamshire (1.3 ML, 3 May 2000), Stone, Staffordshire (1.1 ML, 28 June 2000), Mansfield, Nottinghamshire (0.8 ML, 18 July 2000), Sheffield, South Yorkshire (1.5 ML, 18 September 2000) and Newcastle-Under-Lyme, Staffordshire (1.2 ML, 15 March 2001). These events are probably related to present-day coal mining activity.

(xvi) Elsewhere in the country, seismic events have been reported felt or heard like small earthquakes but, on analysis, have been proved to be sonic booms (Fig. 19). On 20 February 2001, near Montrose, residents of Morphie described "heard a rumble" and "heard a bang. On the following day, BGS received numerous reports that residents in Boulby, Whitby, Scarborough, Filey, Bridlington and Hornsea (approximately 80 km of coastline), felt an event (or events) between 11:20 and 11:40 UTC. Felt reports described "people running into the streets", "a loud bang like an explosion", "windows rattled" and "the whole building shook". The nearest rapid-access networks were examined and no earthquakes were detected at the time. However, a signal consistent with a sonic origin was observed on the microphone at Leeds. The Ministry of Defence confirmed that aircraft were operational. Two other incidents were reported to BGS for which sonic booms were a probable cause but no signals were detected on the rapid-access networks. Despite this absence of data, the felt effects were consistent with those normally received for a sonic event. In the Hartlepool area on the 21 January, numerous people felt an event with reports describing "a very loud bang" and "the ground shook". A local radio station in Northamptonshire, on 20 February, reported that many people in the Corby, Kettering and Thrapston areas felt an event which was described as "a loud bang like an explosion" and "windows rattled and the building shook".

(xvii) Reports have been received of other man-made events. There was one felt explosion reported during the year on 30 August in Largo Bay, Fife. The coastguard confirmed that a 300lb depth charge attached to ordnance was detonated at the time. A seismogram of the event recorded on the network around Edinburgh is shown in Figure 20.

### 5.3 Global earthquakes

The monitoring network detects large earthquakes elsewhere in the world for which selected data is made available to European and international agencies. The past year has been quiet in terms of destructive earthquakes, with only 236 deaths occurring in the year 2000, in contrast to 1999 where over 22,000 deaths occurred. This year, 2001, started with two destructive earthquakes in El Salvador and India. Details are given below.

(i) The most disastrous earthquake during the year 2000, with a magnitude of 8.0 Ms, occurred on 4 June on Sumatra, Indonesia. It caused the deaths of at least 107 people, injured 1,052 more, destroyed or seriously damaged over 12,300 buildings and slightly damaged over 16,900 more in the Bengkulu area of Sumatra and on Enggano Island. The limits of the earthquake damage stretched from about 20 km north of Bengkulu City to a few kilometres south of the town of Manna. Many aftershocks occurred in the region after the 4 June event, including a magnitude 6.7 Mw earthquake on 7 June, which caused the death of 1 person and damaged 600 buildings at Lahat.

(ii) In El Salvador, on 13 January 2001, a magnitude 7.8 Ms earthquake killed over 800 people, injured over 4,500 more and completely or partially destroyed (Fig. 27) over 210,000 homes affecting over 1 million people. The epicentre was in the Pacific Ocean, some 100 km SSE of the capital, San Salvador. A seismogram of the earthquake recorded on the broadband station, near Edinburgh, is shown in Figure 21. It caused major damage in the departments of San Miguel, Santa Ana, La Libertad, La Paz and San Salvador. The most affected area was Las Colinas where a landslide covered over 400 homes completely in mud (Fig. 28). One month later, on February 13, an earthquake with a magnitude of 6.6 Ms occurred in the same general region with an epicentre approximately 30 km east of San Salvador. A further 255 people were killed, over 2,200 more injured and 12,000 more houses were destroyed affecting 83,000 people mainly in the San Vincente and La Paz departments. Both events were felt strongly throughout the region. These two earthquakes along with some 1,900 others form part of an ongoing sequence happening in the area. El Salvador sits on the western part of the Caribbean plate, where it is subducting the Cocos plate. Shallow intraplate (crustal) earthquakes occur within the crust of the overriding Caribbean plate, as in the February 13 event, while deeper intraplate earthquakes occur within the subducting Cocos plate, as in the January 13 event. The cost of the damage, as a result of this sequence of earthquakes, has been estimated at US$3 billion.

(iii) On 26 January 2001, an earthquake with a magnitude of 7.9 Ms, occurred in the region of Gujarat, north west India, approximately 850 km south west of Delhi. It killed at least 20,000 people, injured some 167,000 more and destroyed or damaged over 1 million houses affecting more than 15 million people. The most affected areas were in the Gujarat districts of Bhuj, Kutch, Ahmedabad, Rajkot and Jamnagar (Figs. 29 and 30). A seismogram of the earthquake recorded on the broadband station, near Edinburgh, is shown in Figure 22. The strain that caused this earthquake is due to the Indian plate pushing northward into the Eurasian plate. This northward crustal

**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.

**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.

## 6.2 Storage and Inspection facilities

movement has also caused compression in the Gujarat area resulting in folds and thrust faults running approximately WNW-ESE. It was on one of these thrust faults that the 2001 Gujarat earthquake occurred. The cost of the damage for the earthquake is estimated at US$2.3 billion. This earthquake closely resembles the Rann of Kutch event of 16 June 1819 for which the exact death toll is not known but over 2,000 people were killed in Bhuj alone and some spectacular ground effects were caused including the creation of the 9 metre 'Wall of God' (the Allah Bund).

# 6. The National Seismological Archive (NSA)

## 6.1 Identification, curation and cataloguing

Routine maintenance of the archive has been continued over the past year. There are no major developments to report.

The following section reports on 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).

**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.

The National Seismological Archive has been used by various scientists and researchers world-wide, either visiting in person, or submitting data requests and enquiries through the usual channels.

Collaboration has continued with Dr WHK Lee of IASPEI as a part of an international collaborative effort to publish, electronically, historical seismograms, bulletins, catalogues and other related data for use by the scientific community, to mark the centenary of IASPEI. The results will be presented in Hanoi in August 2001.

The NSA Internet Web pages, with reports available for reading online or for download, database search page and descriptions of the main collections, continue to be the first resource for researchers wishing to make use of the archive. The address is: http://www.gsrg.nmh.ac.uk/hazard/nsahome.htm.

### 6.3 Digital records

The programme of digitising old 1" analogue tapes is continuing following the upgrade of computer digitising software but it is proving difficult to extract data owing to the condition of the tapes and old replay equipment.

## 7. Dissemination of results

### 7.1 Near-immediate response

Customer Group members have continued to receive seismic alerts by fax (Annex C) whenever an event has been reported to be felt or heard by more than two individuals. In the case of series of events in coalfield areas, only the more significant ones are reported in this way. Some 35 alerts have been issued to the Customer Group during the year.

The bulletin board, on a captive process on the central computer in Murchison House, has continued to be maintained on a routine basis for UK and global earthquake information. It contains continually updated seismic alert information together with the most recent 3 months, at least, of provisional data from the routine analysis of the UK network. Throughout the year, an updated catalogue listing of recent earthquakes (1 month) and seismic alerts, giving details of UK and global earthquakes, has been available through an Internet home page (address: http://www.gsrg.nmh.ac.uk). Questionnaires and updated information on the Warwick earthquake was also made available on the home page. Feedback suggests that the Global Seismology web site is being used extensively for the wide variety of seismological information it offers. In the past year, some 172,000 visits have been logged, an increase of over 30% 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 phenomena. Most of the UK is now covered in this way for earthquakes with magnitudes of 2.0 ML or greater.

### 7.2 Medium-term response

Preliminary bulletins of seismic information have continued to be produced and distributed on a routine basis to the Customer Group within 6 weeks of the end of a 1 month reporting period.

### 7.3 Longer-term

The project aim is to publish the revised annual Bulletin of British Earthquakes within 6 months of the end of a calendar year. For 2000, it was issued within 4 months.

## 8. Programme for 2001/02

During the year, the project team (Annex D) will continue to detect, locate and understand natural seismicity and man-made events in and around the UK and to supply timely information to the Customer Group. 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 the station coverage and capabilities. Specific advances anticipated for 2001/02, subject to the continuation of funding at least at the current level and without any unexpected closures of site specific networks, are:

(i) Further installation of the QNX operating system.

(ii) Upgrade of four stations to the broadband standard with high dynamic range 24-bit digitizers and Internet connections to Edinburgh.

(iii) Upgrade of three-component short period 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 to secure further broadband data.

(vi) Maintenance of 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.

## 9. 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 D) 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).

## 10. References

**References:**

Firth, C.R. and Stewart, I.S., 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. *Quaternary Science Reviews*, Vol. 19 (14-15) (2000) pp. 1469-1493

Musson, R.M.W., 1994. A Catalogue of British Earthquakes. Brit.Geol.Surv. Tech. Rep. No. WL/94/04.

Musson R.M.W. and Winter P.W., 1997. Seismic hazard maps for the UK, Natural Hazards, vol 14 pp 141-154.

Musson, R.M.W., 1997. Seismic hazard studies in the UK: Source specification problems of intraplate seismicity, Natural Hazards, vol 15, pp 105-119.

Musson, R.M.W., 2000. Evaluation of seismic hazard source models, in Lapajne, J. and Vidrih, R. (eds), Seismicity modelling in seismic hazard mapping, Slovenian Geophysical Survey, Ljubljana, pp 53-66.

Simpson, B.A., (editor), 2001. Bulletin of British earthquakes 2000, Brit.Geol.Surv. Tech. Rep. No. IR/01/28.

**Stewart, I.S.**, Sauber, J. & Rose, J. (Eds.) 2000. *Ice Sheets, Crustal Deformation and Seismicity*, Quaternary Science Reviews special issue, vol. 14/15. Available on-line http://www.elsevier.nl/inca/publications/store/6/3/6/

**Stewart, I.S.**, Firth, C.R., Rust, D.J., Firth, J.F. & Collins, P.E.F. (in press) Postglacial fault movement and palaeoseismicity in western Scotland: A reappraisal of the Kinloch Hourn Fault, Kintail. *Journal of Seismology.*

Yuan, X.N.J., Kind, R., Mechie, J. and Sandvol, E., 1997. Lithospheric and upper mantle structure of southern Tibet from a seismological passive source experiment. *Jo. Geophys. Res.,* ***102***, 27491-27500.

**Table 1**
**Measured Ground Accelerations Recorded on Strong Motion Instruments in the UK**
**1994 - March 2001**

| 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 |

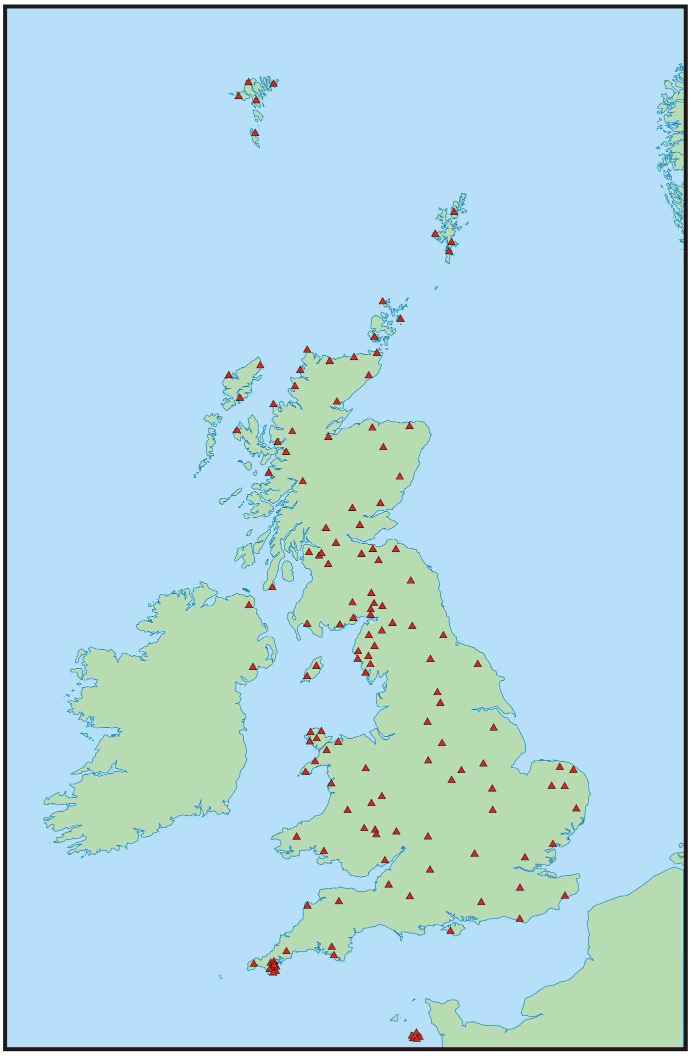


**Figure 1.** BGS rapid access seismograph network operational March 2001.

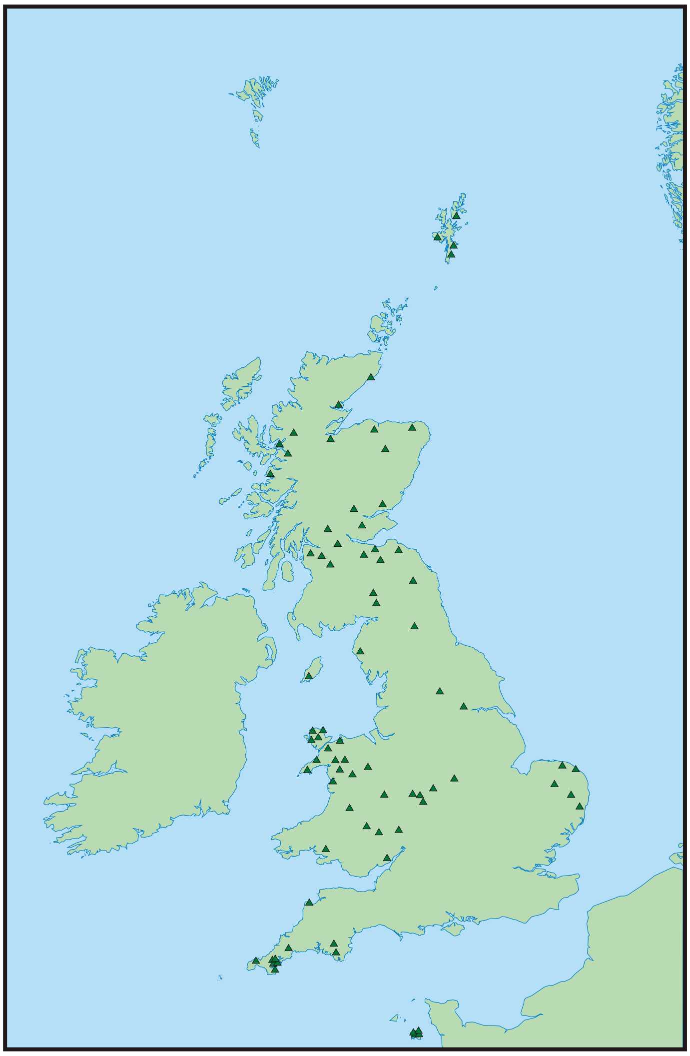
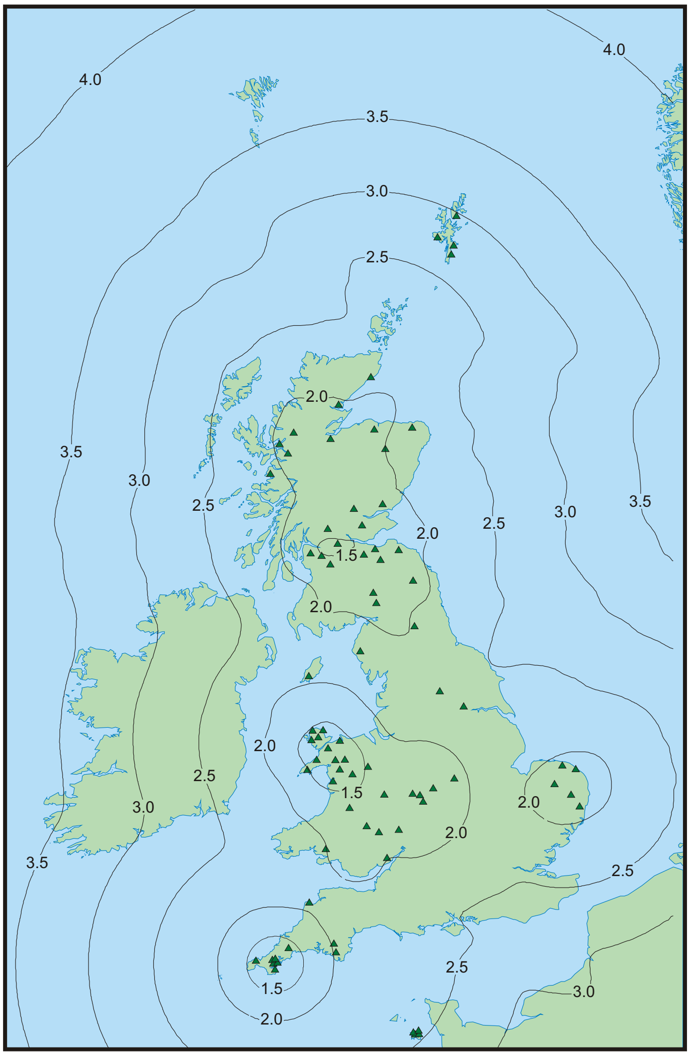


**Figure 2.** BGS seismograph network in 1988 prior to the commencement of the UK monitoring enhancement project.

**Figure 3.** Detection capability of network, March 2001. Contour values are Richter local magnitude (ML) for 20 nanometres of noise and S-wave amplitude twice that at the fifth nearest station.



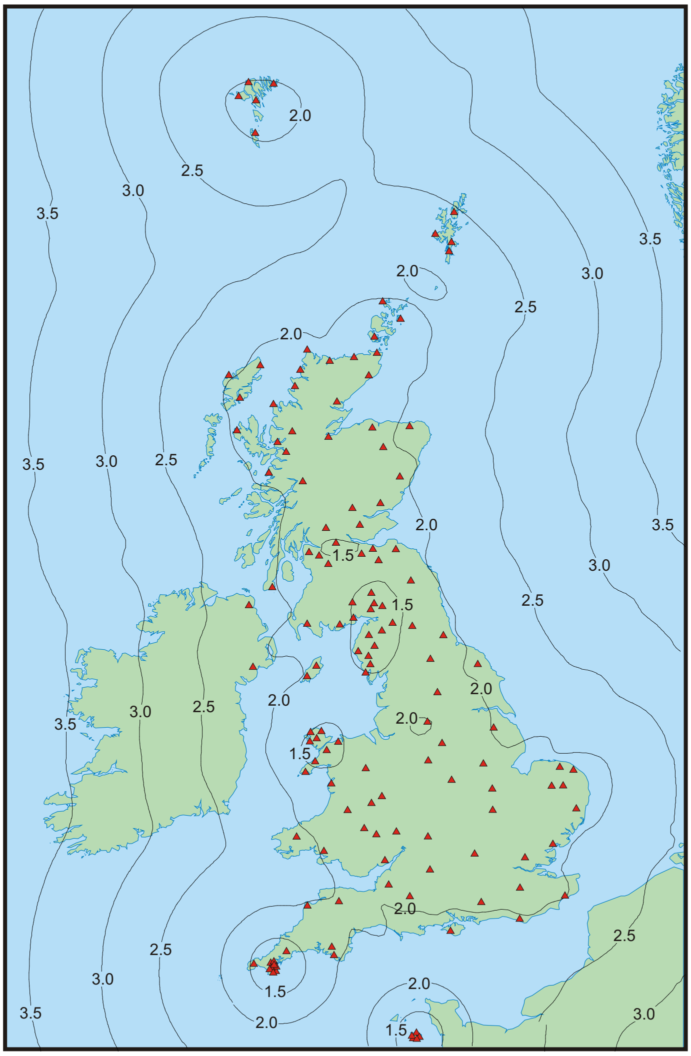




**Figure 4.** Detection capability of network, 1988. Contour values are Richter local magnitude (ML) for 20 nanometres of noise and S-wave amplitude twice that at the fifth nearest station.

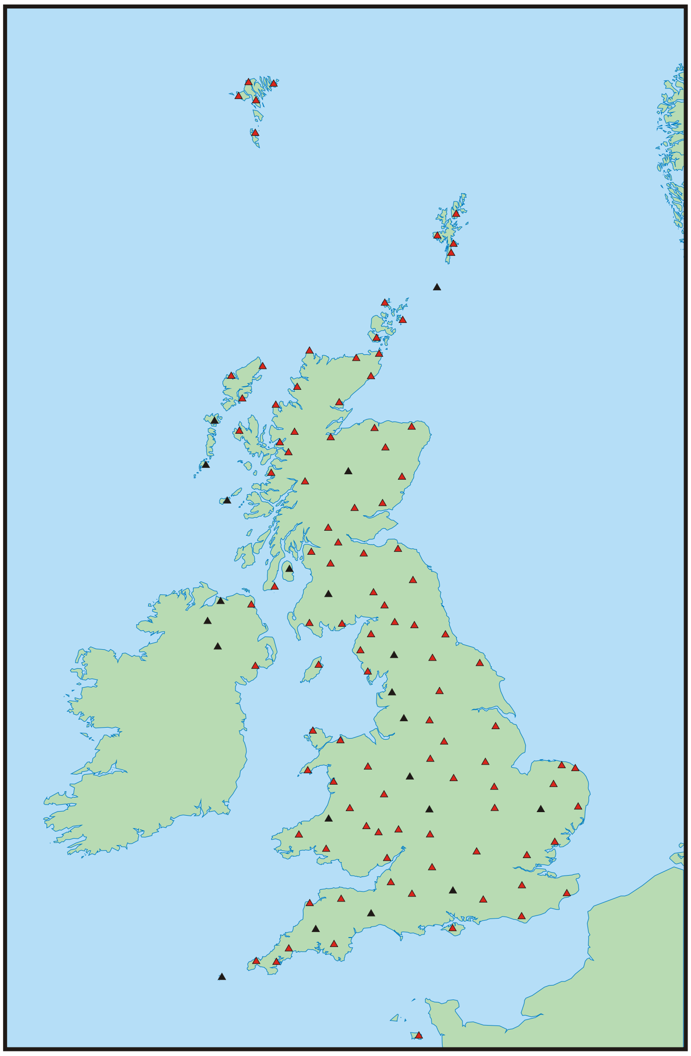


**Figure 5.** Proposed long-term background seismic monitoring network with an average station spacing of 70 km. Colour coding shows existing coverage (red) and proposed stations (black).

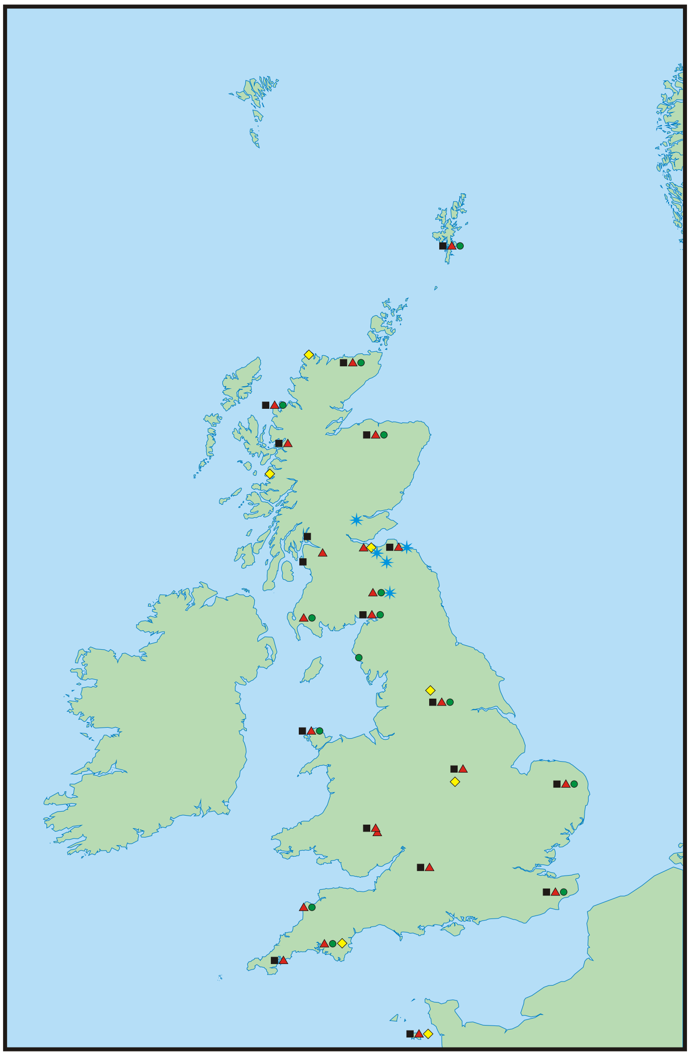


**Figure 6.** BGS network of strong motion instruments (black), low sensitivity (red), broadband (yellow - removed September 2000), microphones (green) and environmental stations (blue) in March 2001.

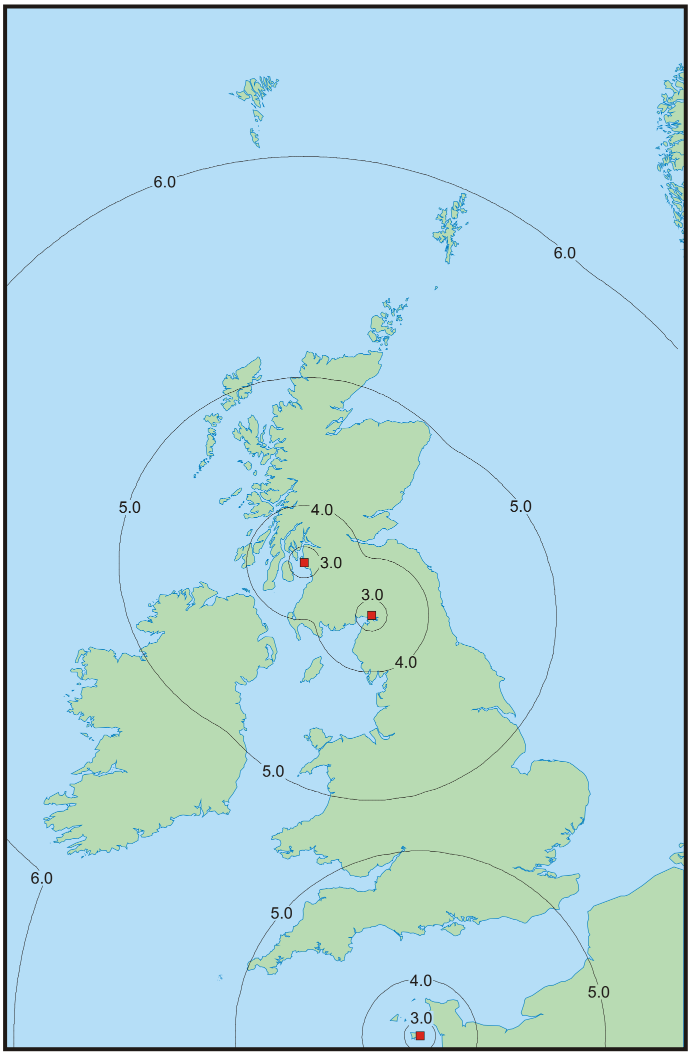



**Figure 7.** Minimum Richter local magnitude (ML) detectable by the strong motion network operational December 1992.

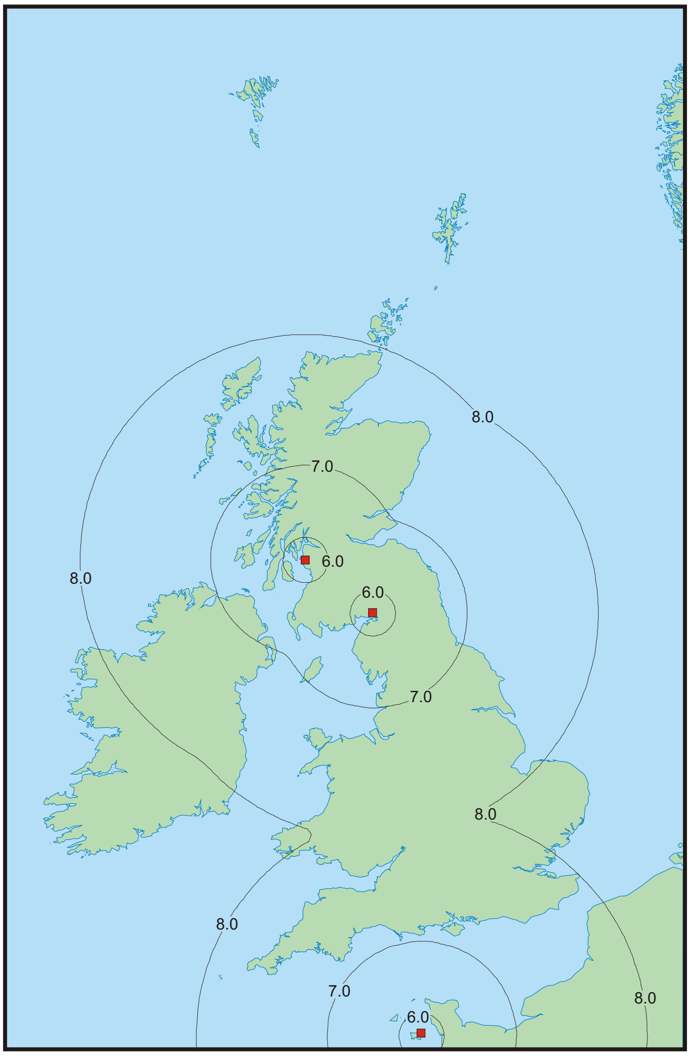



**Figure 8.** Maximum Richter local magnitude (ML) measurable by the strong motion network operational December 1992.

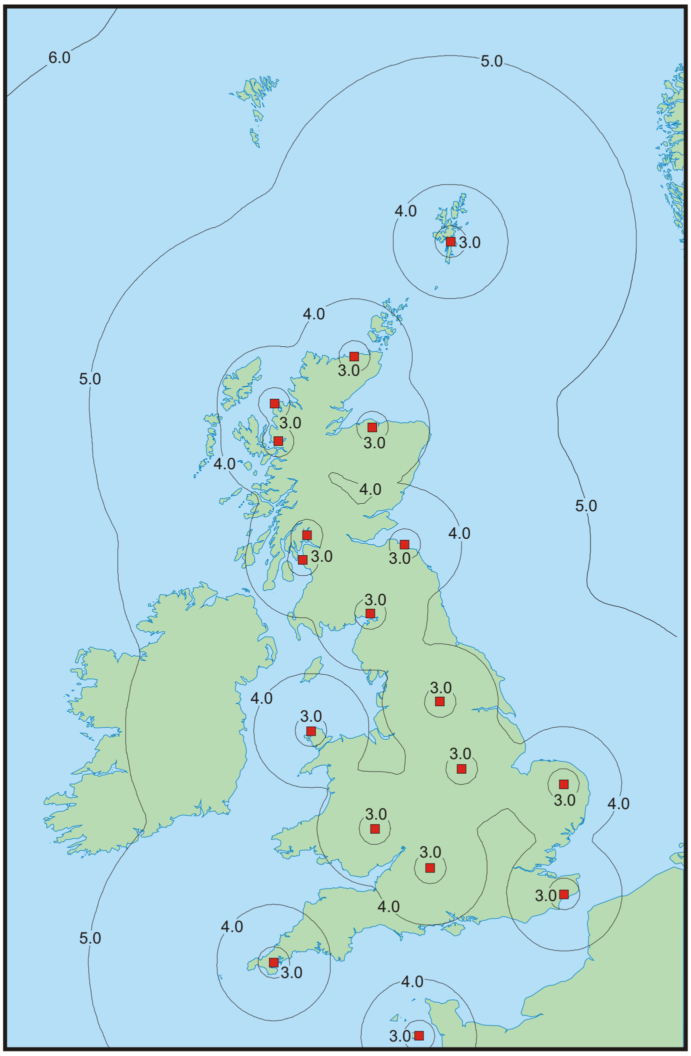



**Figure 9.** Minimum Richter local magnitude (ML) detectable by the strong motion network operational March 2001.

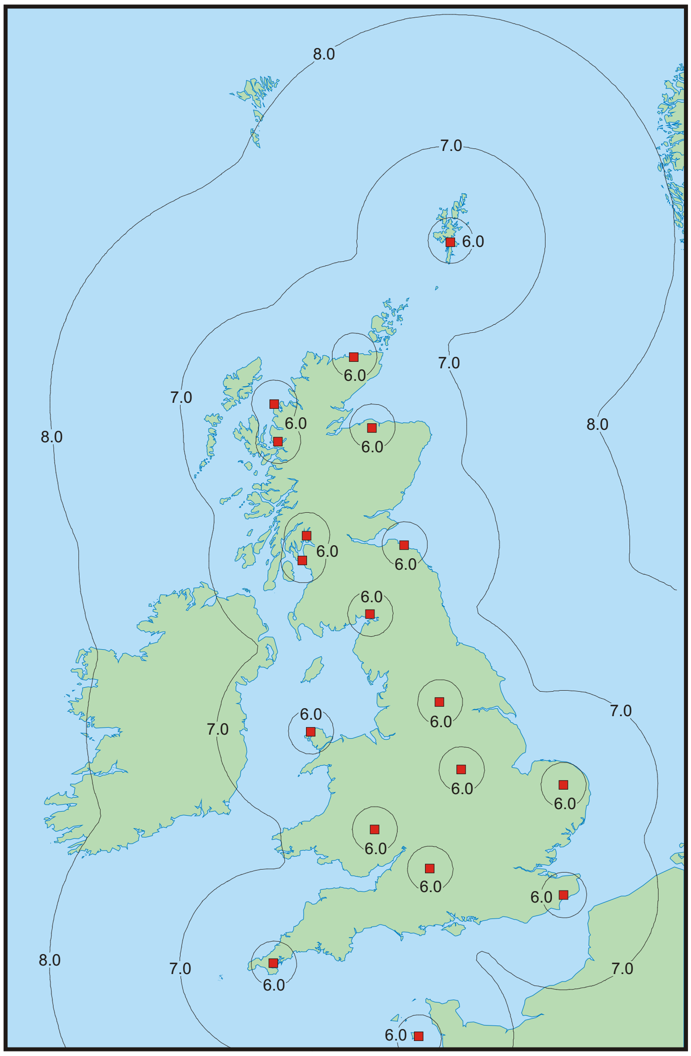



**Figure 10.** Maximum Richter local magnitude (ML) measurable by the strong motion network operational March 2001.

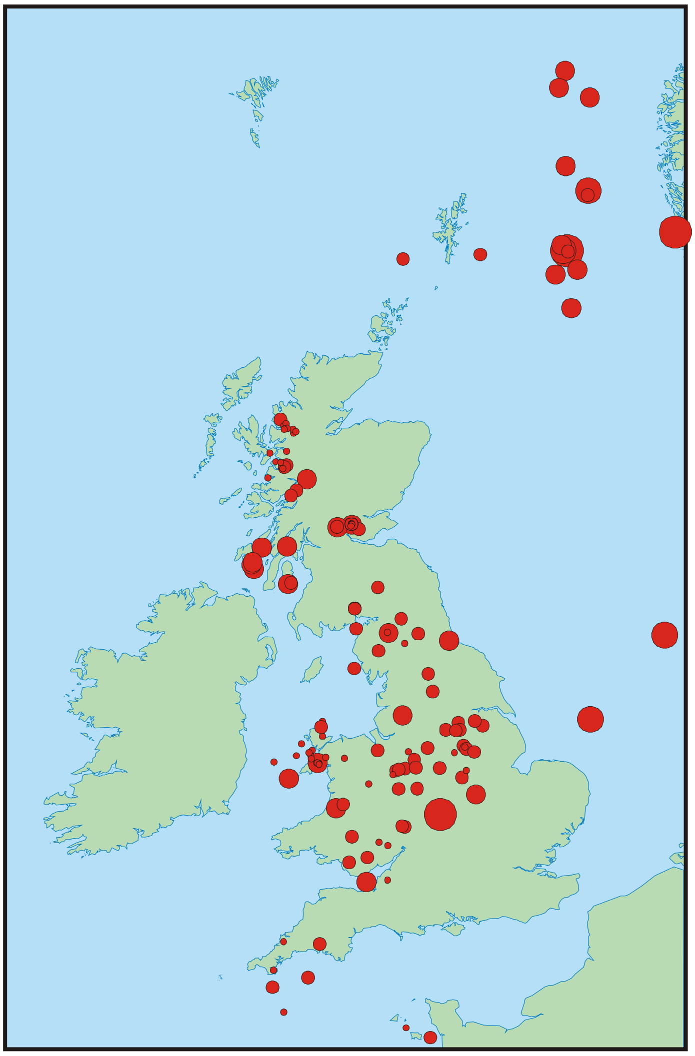


**Figure 11.** Epicentres of all UK earthquakes located in 2000.

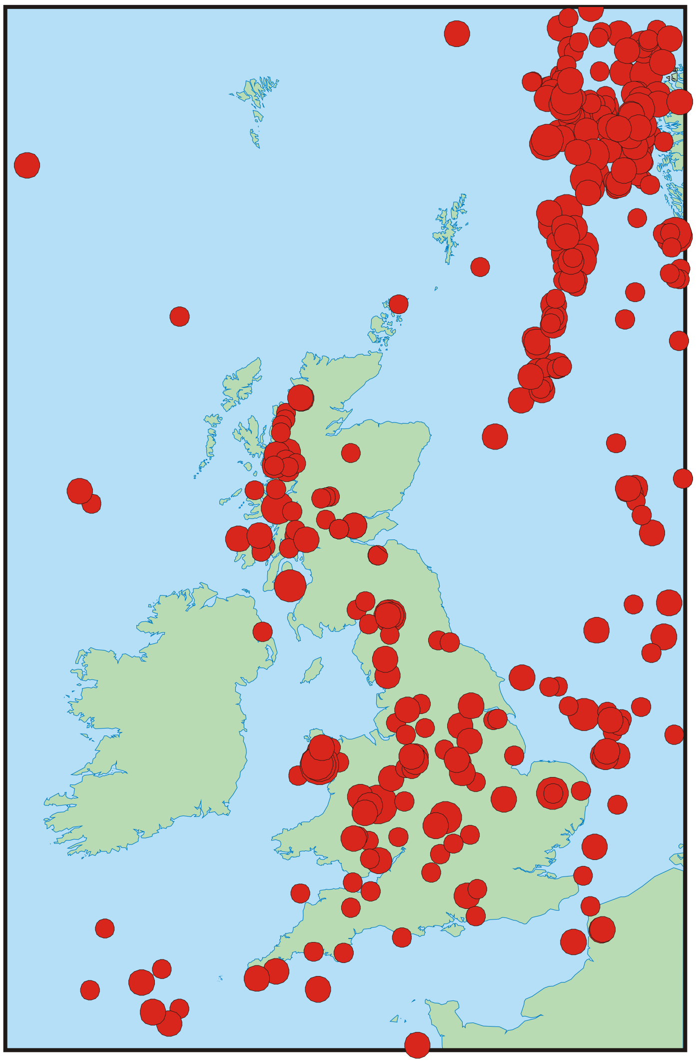


**Figure 12.** Epicentres of earthquakes with magnitudes 2.5 ML or greater, for the period 1979 to March 2001

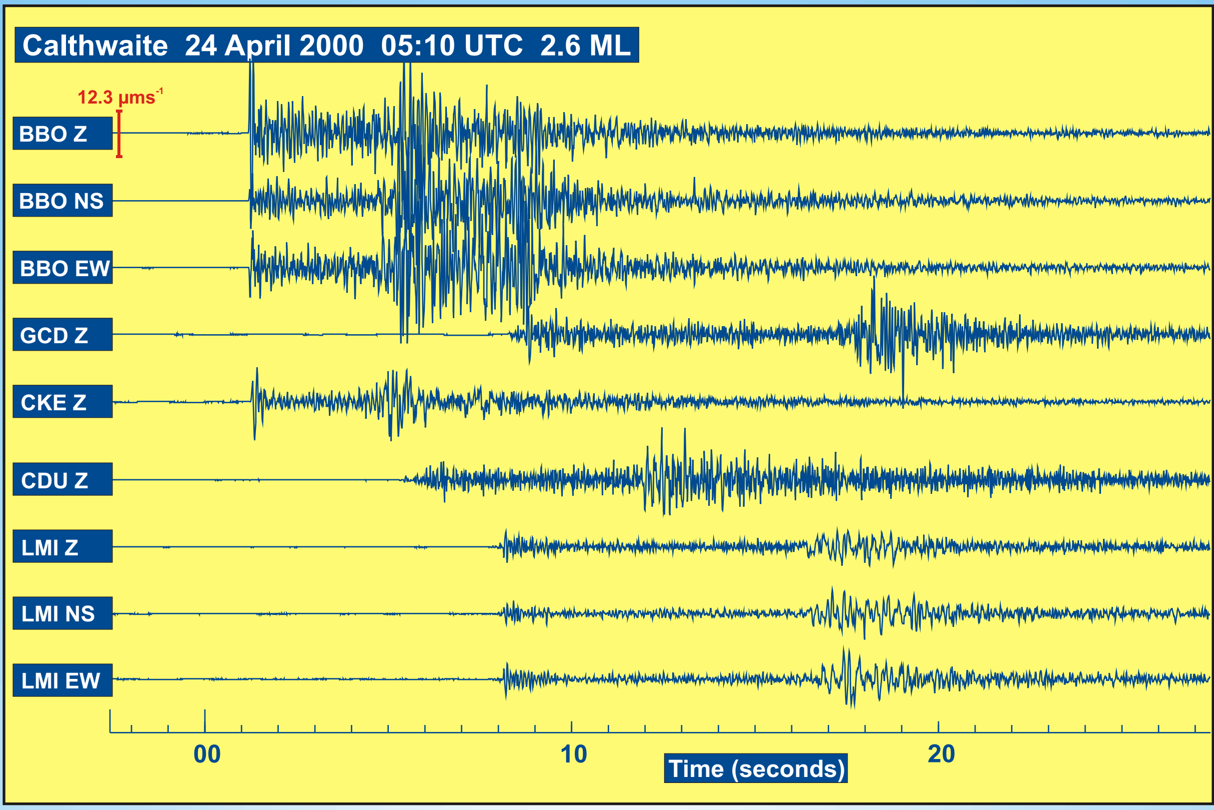



**Figure 13.** Seismograms recorded on the Cumbria network from the magnitude 2.6 ML earthquake felt in the Calthwaite area on 24 April 2000 05:10 UTC. Three letter codes refer to stations in Annex E.

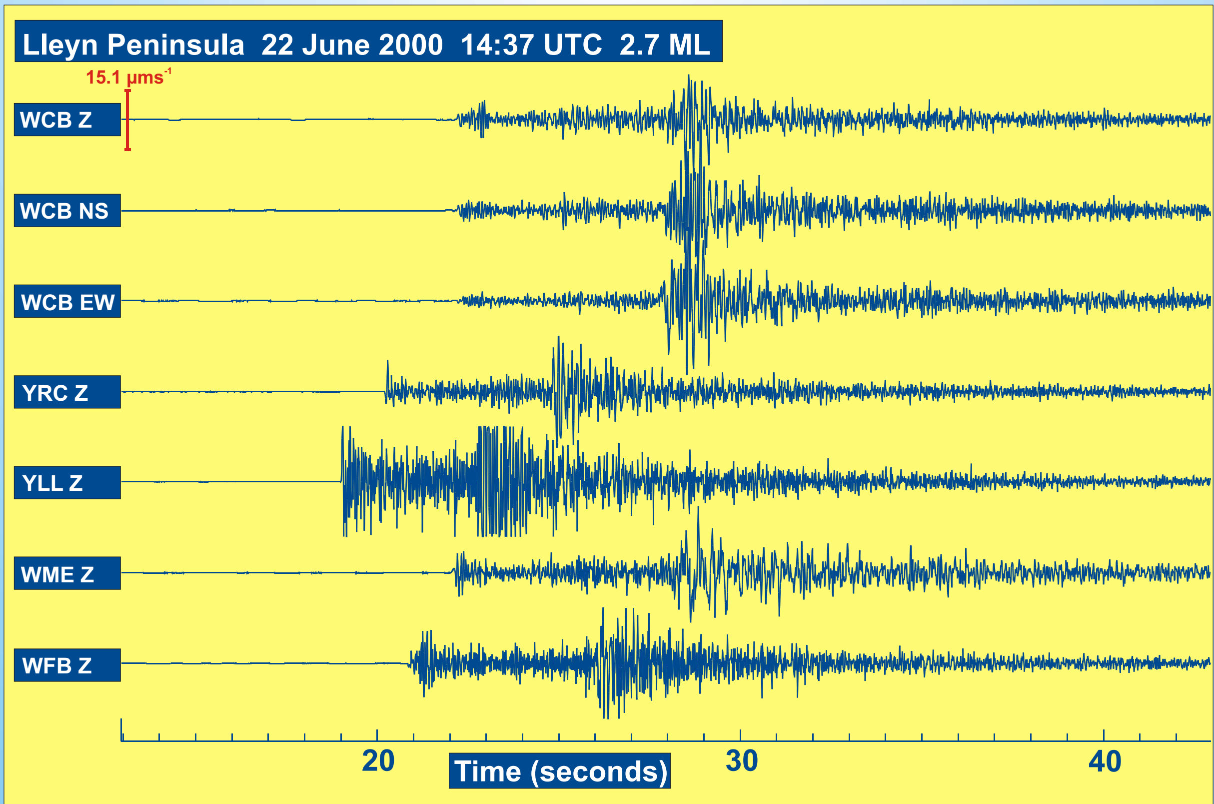



**Figure 14.** Seismograms recorded on the North Wales network from the magnitude 2.7 ML earthquake felt in the Gwynedd area on 22 June 2000 14:37 UTC. Three letter codes refer to stations in Annex E.

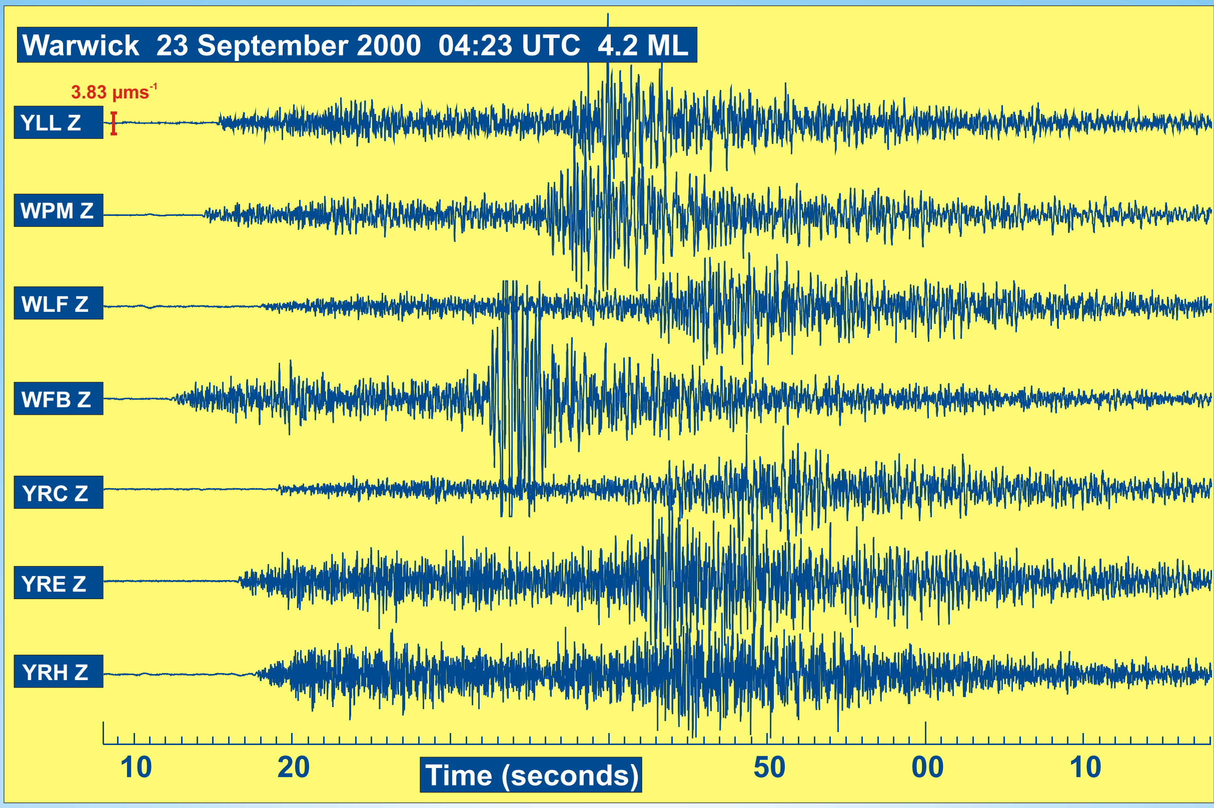



**Figure 15.** Seismograms recorded on the North Wales network from the magnitude 4.2 ML earthquake felt throughout the Midlands area on 23 September 2000 04:23 UTC. Three letter codes refer to stations in Annex E.

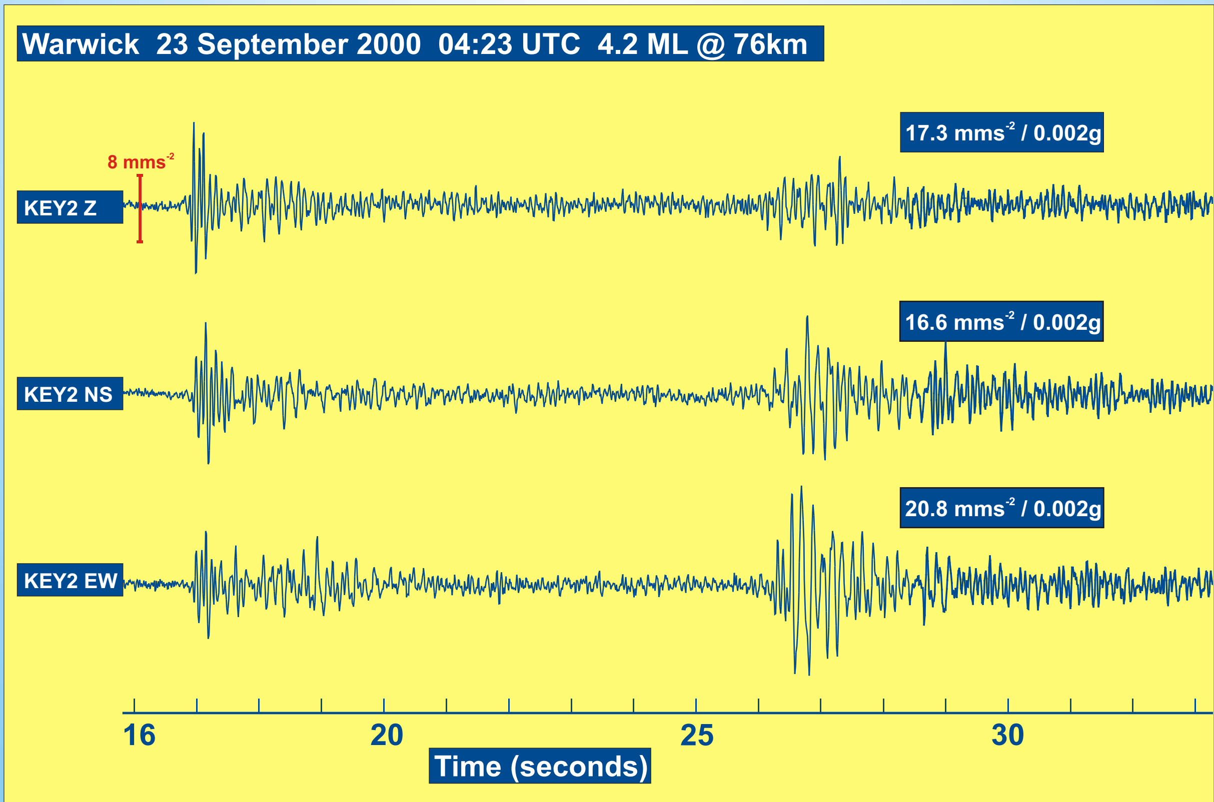



**Figure 16.** Seismograms recorded on the strong motion instruments near Keyworth from the Warwick earthquake with a magnitude of 4.2 ML on 23 September 2000 04:23 UTC. Three letter codes refer to stations in Annex E.

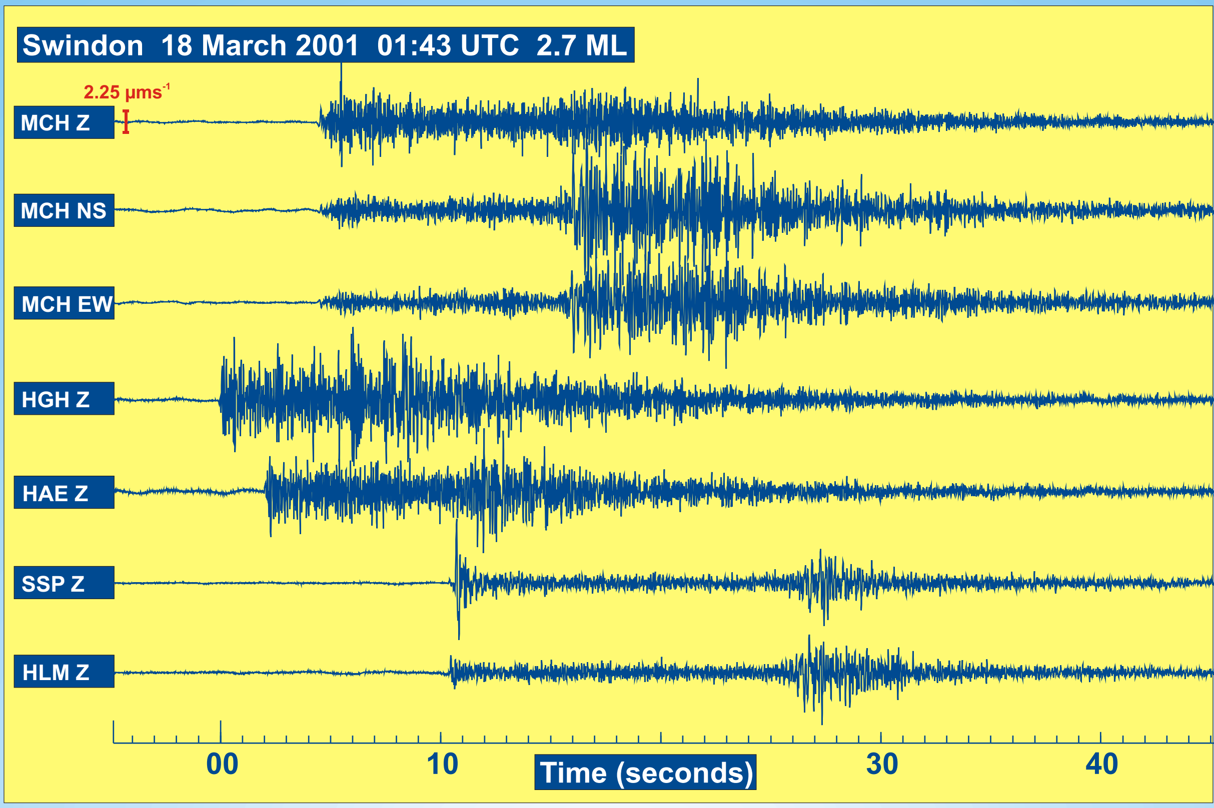



**Figure 17.** Seismograms recorded on the Hereford network from the magnitude 2.7 ML Swindon earthquake on 18 March 2001 01:43 UTC. Three letter codes refer to stations in Annex E.

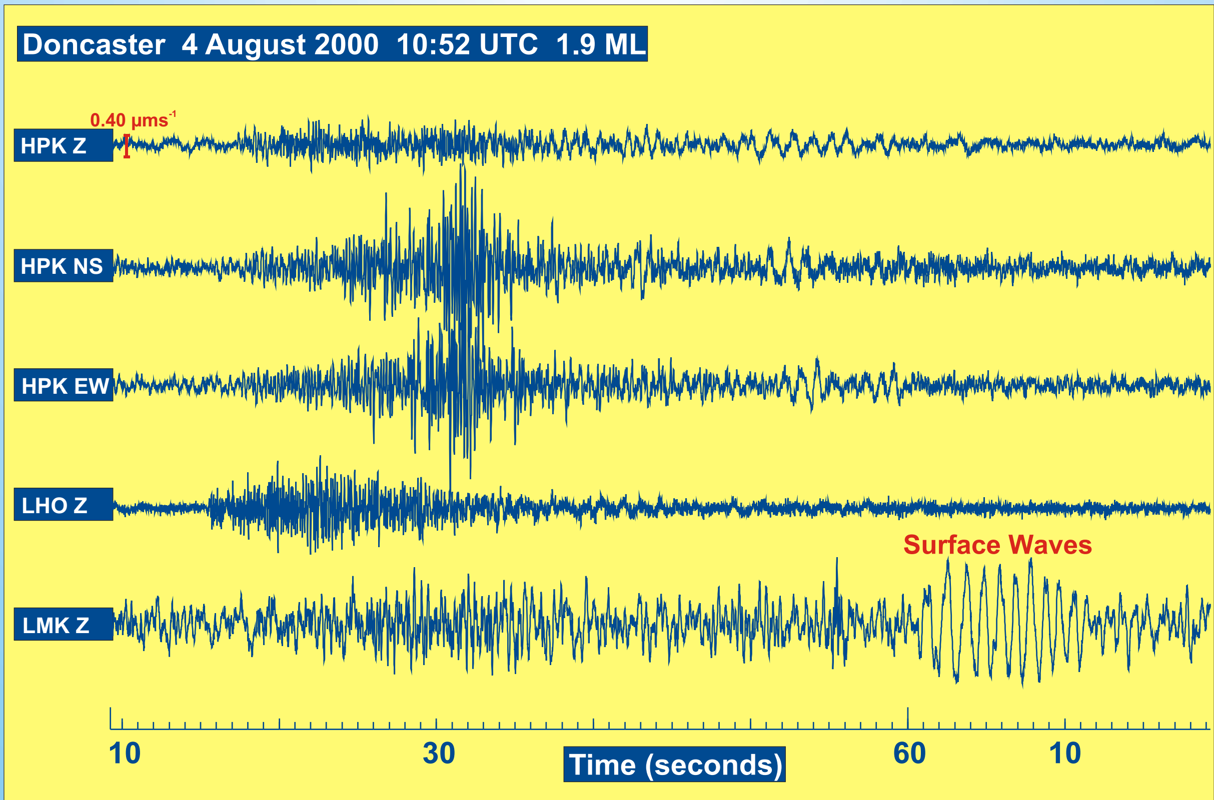



**Figure 18.** Seismograms recorded on the Leeds network from the magnitude 1.9 ML earthquake felt in the Doncaster area on 4 August 2000 10:52 UTC. Three letter codes refer to stations in Annex E.

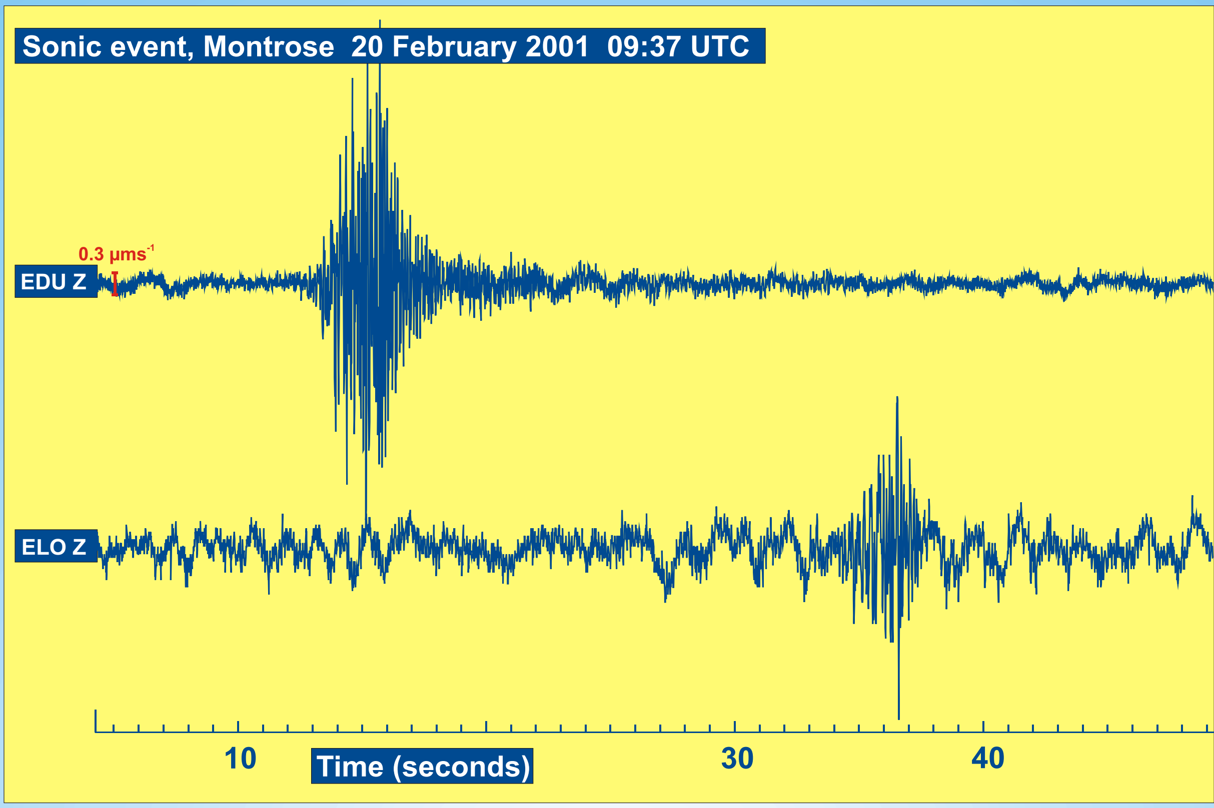



**Figure 19.** Seismograms recorded on the LOWNET (Edinburgh) network from the sonic event felt in the Montrose region on 20 February 2001 09:37 UTC. Three letter codes refer to stations in Annex E.

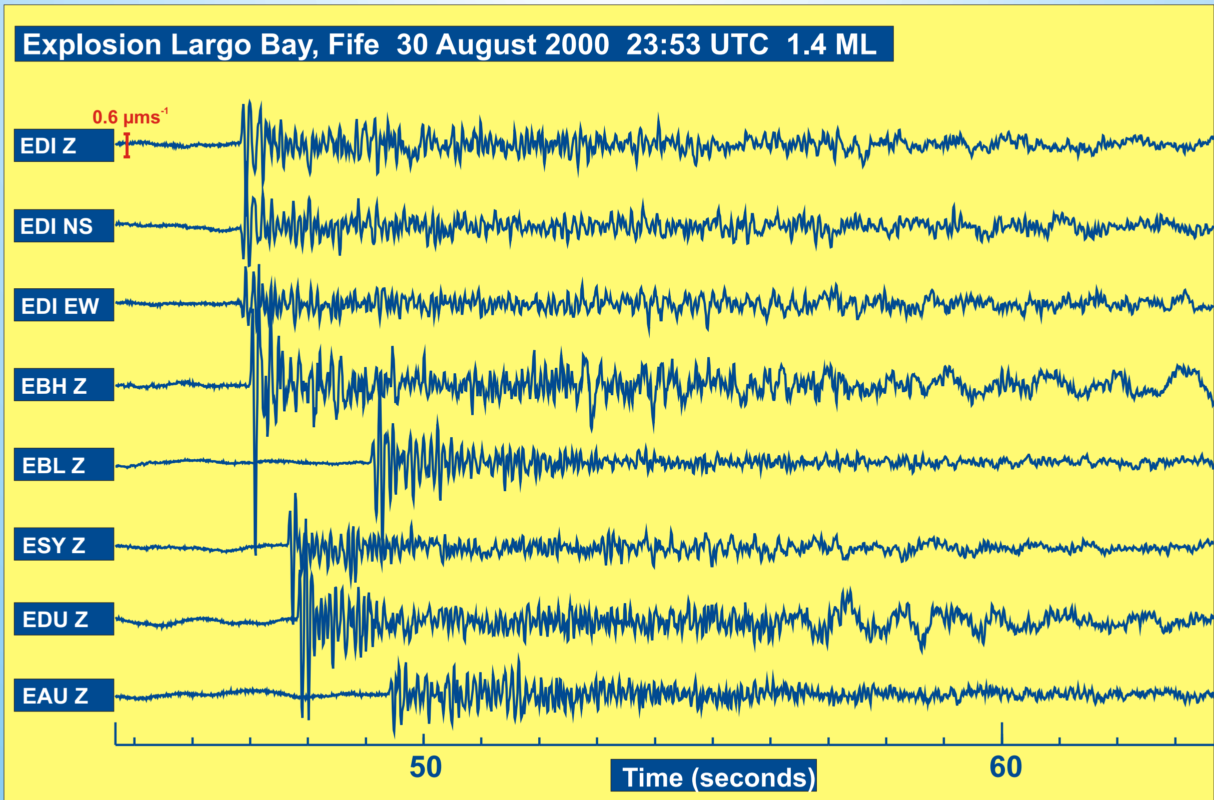



**Figure 20.** Seismograms recorded on the LOWNET (Edinburgh) network from the magnitude 1.4 ML explosion felt in the Leven area on 30 August 2000 23:53 UTC. Three letter codes refer to stations in Annex E.

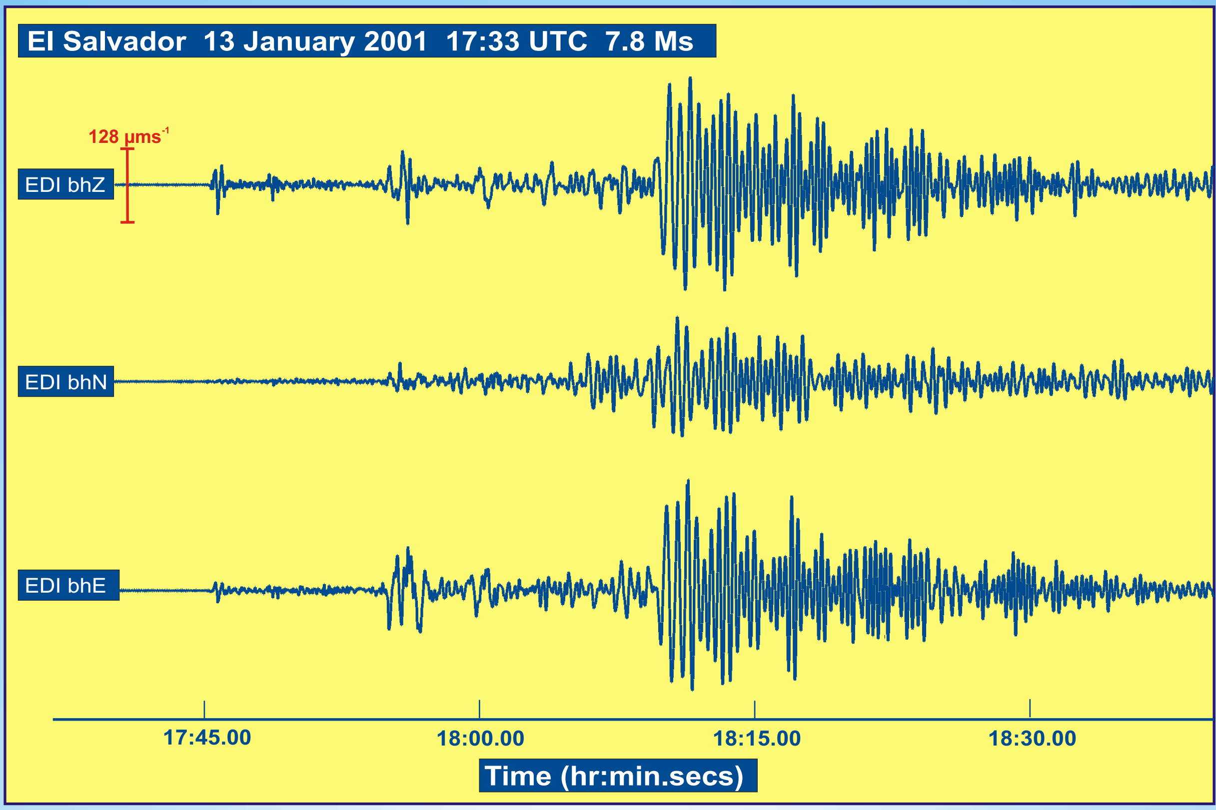



**Figure 21.** Seismograms recorded on the broadband instruments near Edinburgh from the El Salvador earthquake with a magnitude of 7.8 Ms on 13 January 2001 17:33 UTC. Three letter codes refer to stations in Annex E.

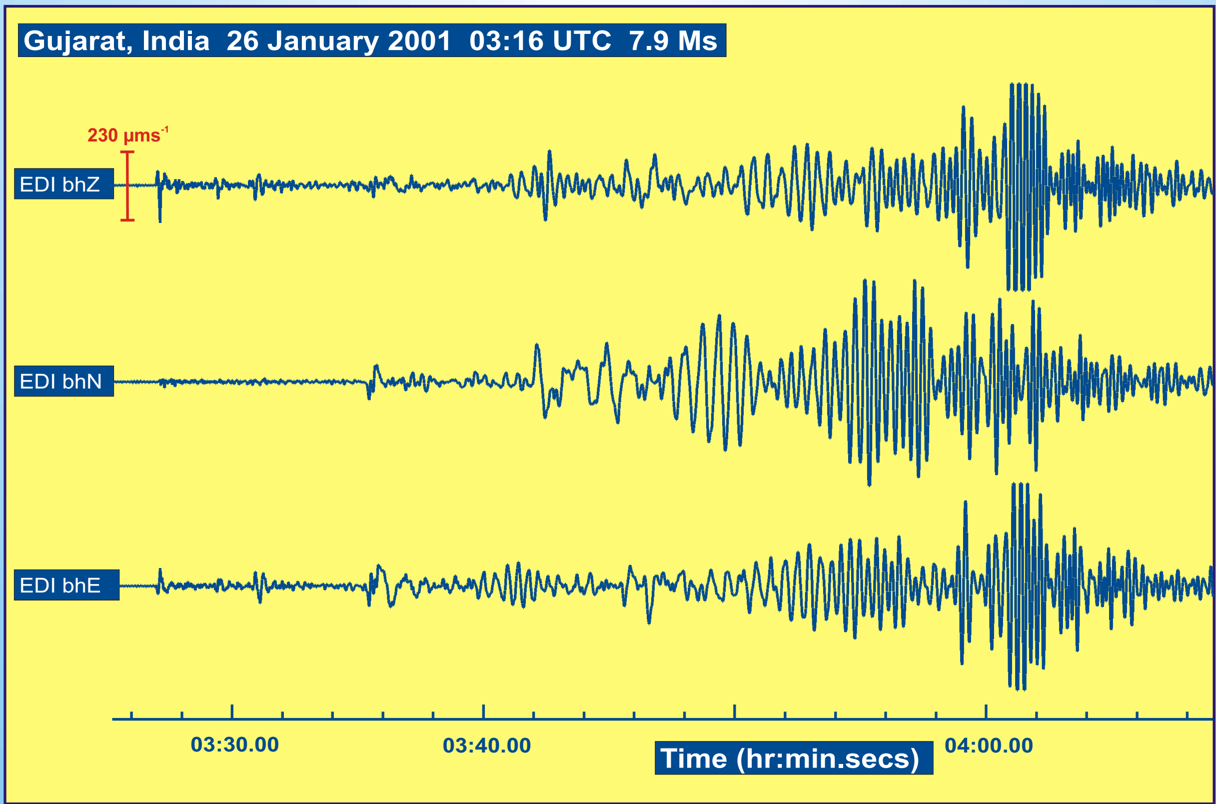



**Figure 22.** Seismograms recorded on the broadband instruments near Edinburgh from the Gujarat, India earthquake with a magnitude of 7.9 Ms on 26 January 2001 03:16 UTC. Three letter codes refer to stations in Annex E.

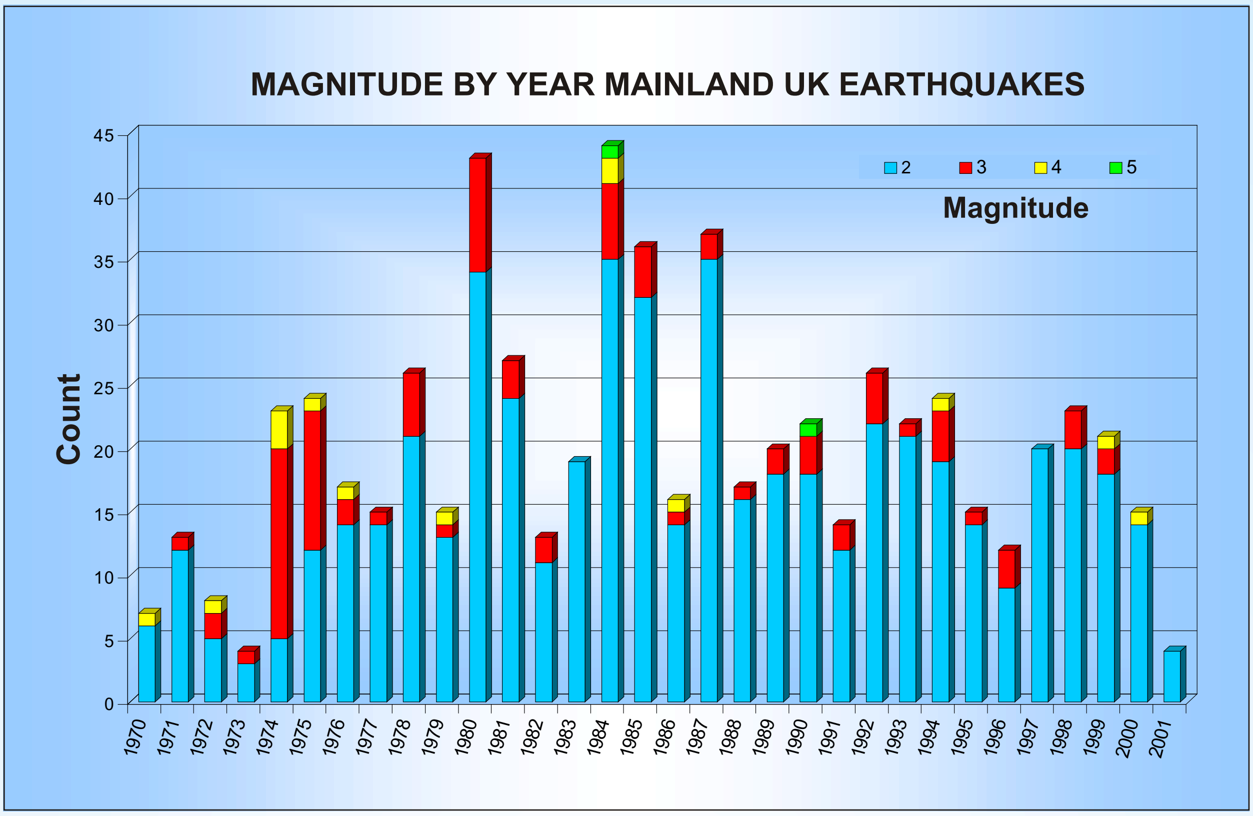



**Figure 23.** Histogram showing number of events magnitude 2.0 ML or above detected, 1970 - March 2001.

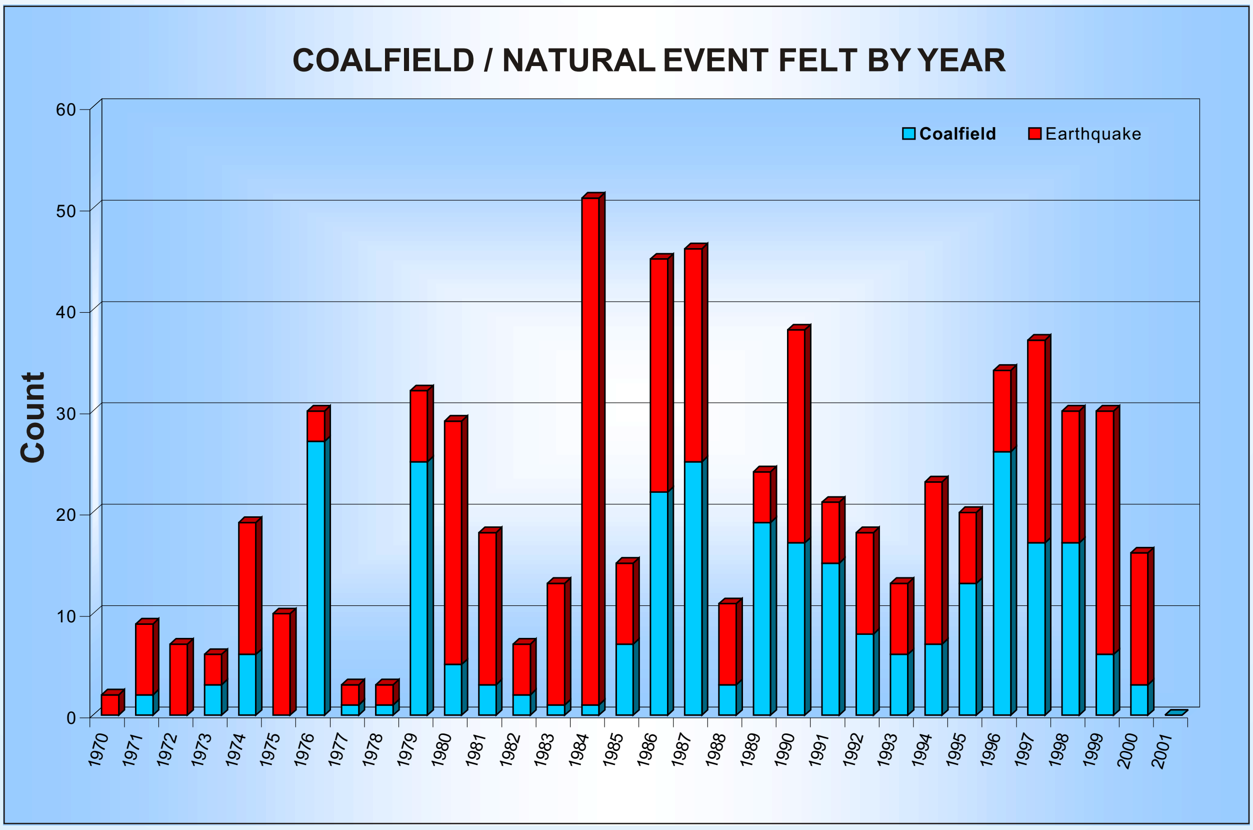



**Figure 24.** Histogram showing number of felt events 1970 - March 2001.

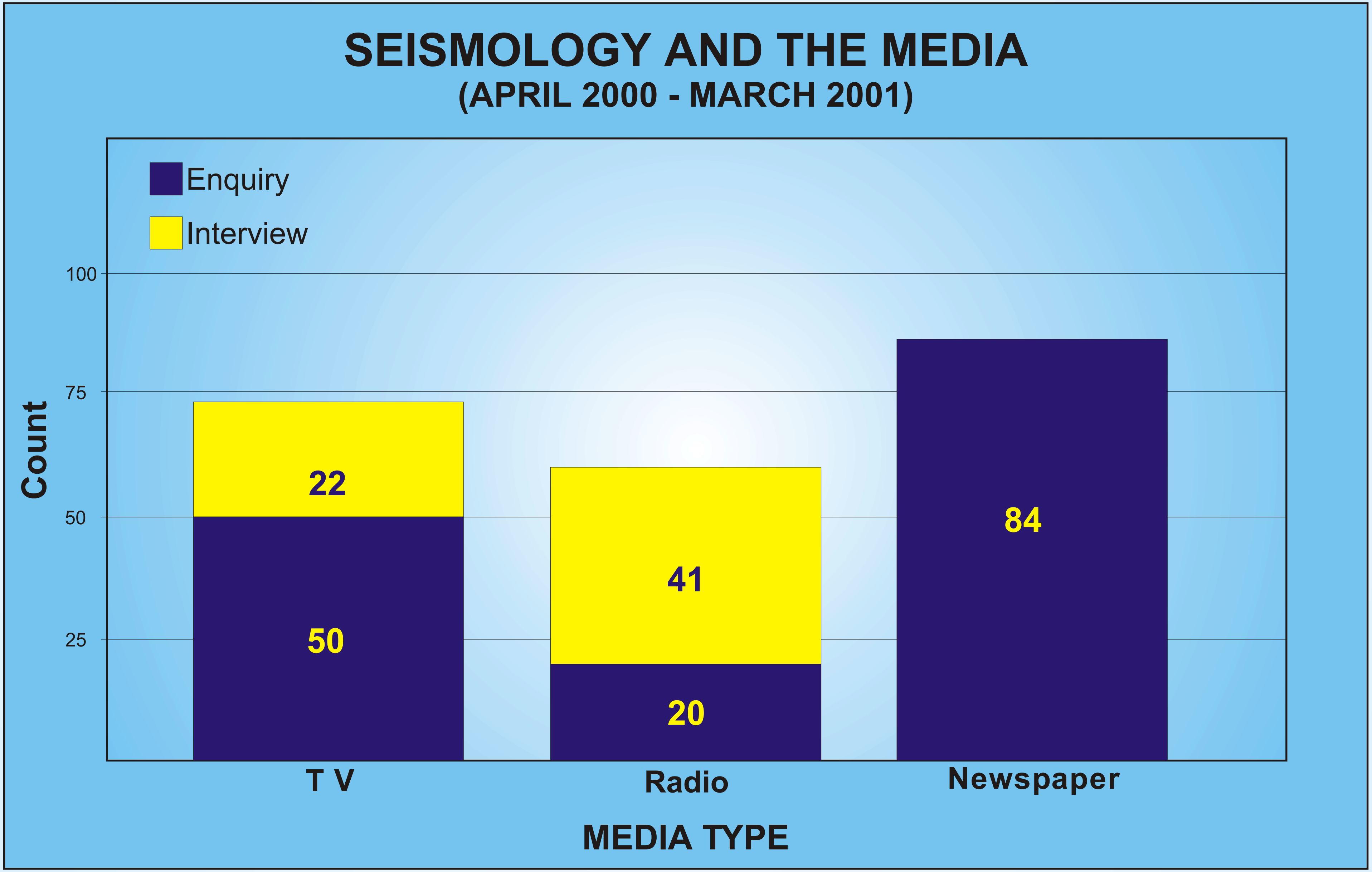



**Figure 25.** Histogram showing number of media enquiries answered for significant UK and world earthquakes between April 2000 and March 2001.

# Warwick Earthquake 23 September 2000 04:23 UTC 4.2 ML

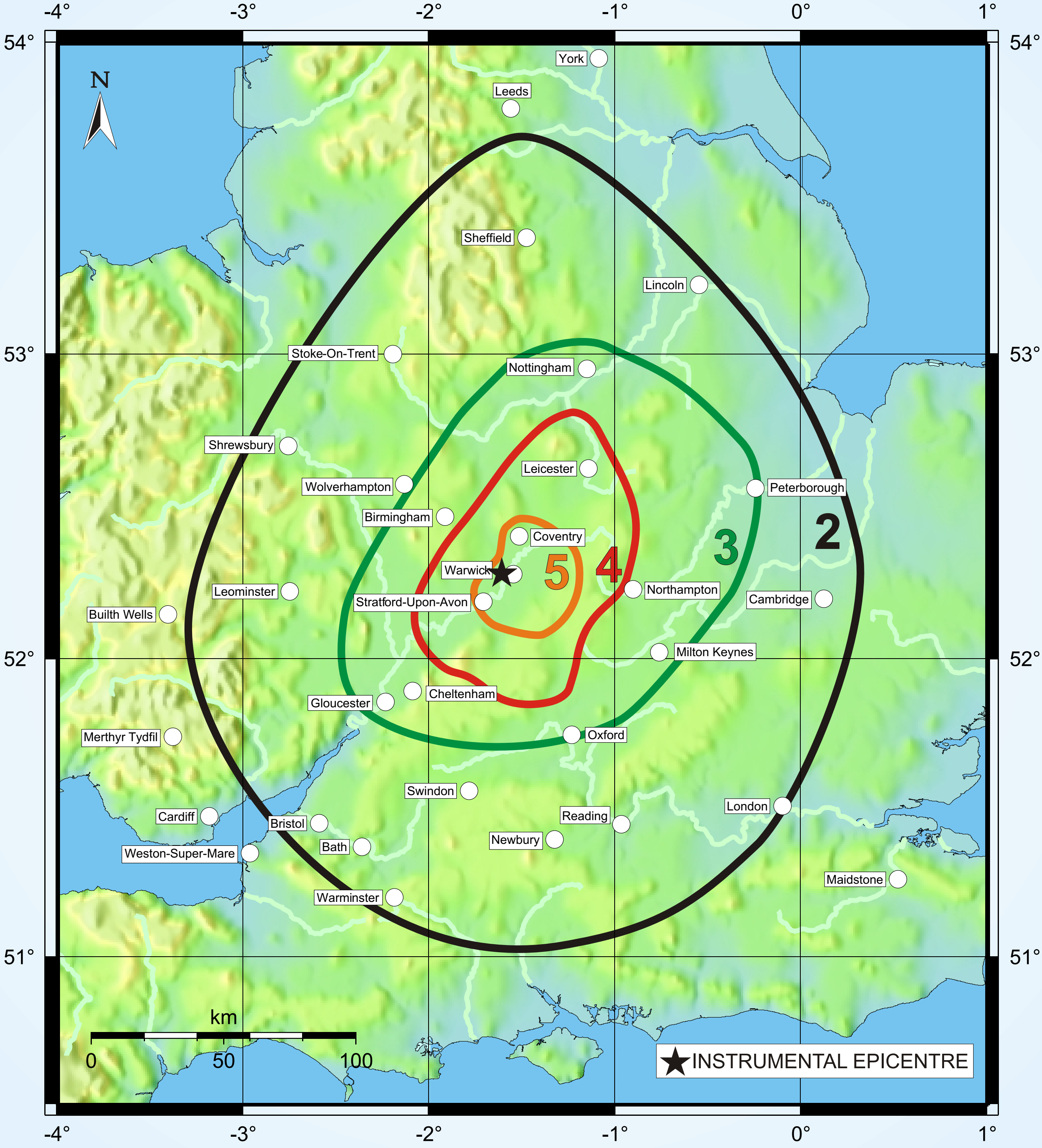



**Figure 26.** Map of the felt effects of the Warwick earthquake 23 September 2000 04:23 UTC, magnitude 4.2 ML - EMS Intensities.

**Figure 27.** Damage in the town of Santiago de Maria, El Salvador from the El Salvador earthquake 13 January 2001 17:33 UTC, magnitude 7.8 Ms. (Photograph supplied by Dr Julian Bommer, Imperial College, London/PRISMA).

**Figure 28.** Damage in the Las Colinas region from the El Salvador earthquake 13 January 2001 17:33 UTC, magnitude 7.8 Ms. (Copyright Associated Press).

**Figure 29.** Earthquake damage in the Bhuj region from the Gujarat, India earthquake 26 January 2001 03:16 UTC, magnitude 7.9 Ms. (Photograph supplied by Andy Thompson, Arup Advanced Technology, EEFIT Mission).

**Figure 30.** Earthquake damage in the Bhuj region from the Gujarat, India earthquake 26 January 2001 03:16 UTC, magnitude 7.9 Ms. (Photograph supplied by Andy Thompson, Arup Advanced Technology, EEFIT Mission).

## CONTRIBUTORS TO THE PROJECT

British Energy

British Nuclear Fuels plc

BNFL Magnox Generation

Department of the Environment, Transport and the Regions

Faroese Museum of Natural History

GEM Oil Industry Consortium

Health and Safety Executive

Natural Environment Research Council

Nuclear Installations Inspectorate

Renfrewshire Council

Scottish Coal

Scottish and Southern Energy plc

United Kingdom Atomic Energy Authority

Welsh Assembly

Western Frontiers Association

Atomic Weapons Establishment (Data only)

**Customer Group Members (not contributing in Year Twelve)**

British Gas/Transco

International Seismological Centre

Scottish Office

United Kingdom Nirex Limited

University of Exeter

# EARTHQUAKES WITH MAGNITUDE 2.0 AND ABOVE, RECORDED IN THE UK AND OFFSHORE WATERS:2000

| YearMoDy | HrMnSecs | Lat | Lon | kmE | kmN | Dep | Mag | Locality | Int | No | DM | Gap | RMS | ERH | ERZ | SQD | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20000125 | 104813.7 | 53.64 | -2.47 | 369.0 | 416.0 | 8.0 | 2.0 | BOLTON, GTR MANCHESTER | | 9 | 42 | 89 | 0.11 | 0.6 | | C*C | |
| 20000211 | 021617.9 | 54.58 | 3.61 | 762.4 | 534.9 | 20.0 | 3.2 | SOUTHERN NORTH SEA | | 16 | 249 | 279 | 0.23 | 7.5 | 11.2 | D*D | |
| 20000212 | 085128.5 | 55.91 | -5.31 | 193.1 | 673.5 | 8.8 | 2.7 | LOCHGILPHEAD, S'CLYDE | 5+ | 13 | 36 | 135 | 0.11 | 0.5 | 2.9 | B*C | FELT KAMES... |
| 20000212 | 185106.2 | 52.35 | -3.95 | 267.5 | 274.4 | 4.4 | 2.0 | ABERYSTWYTH, DYFED | | 12 | 37 | 88 | 0.19 | 0.8 | | C*C | 7KM SE OF ABERYSTWYTH |
| 20000216 | 060251.5 | 55.88 | -5.92 | 154.6 | 671.8 | 12.5 | 2.2 | JURA, STRATHCLYDE | | 9 | 63 | 175 | 0.17 | 1.9 | 4.4 | B*D | |
| 20000220 | 093152.3 | 56.20 | -4.10 | 269.7 | 702.6 | 4.6 | 2.3 | DOUNE, CENTRAL | 4+ | 14 | 15 | 132 | 0.04 | 0.2 | 0.4 | A*C | FELT DOUNE... |
| 20000411 | 022613.5 | 59.23 | 2.09 | 633.4 | 1044.8 | 8.1 | 2.1 | NORTHERN NORTH SEA | | 16 | 180 | 176 | 0.20 | 1.4 | 2.0 | B*D | |
| 20000414 | 192733.5 | 56.84 | -4.90 | 223.3 | 775.7 | 12.1 | 2.1 | FORT WILLIAM, HIGHLAND | | 8 | 5 | 127 | 0.07 | 0.8 | 0.8 | A*B | 12KM E OF FORT WILLIAM |
| 20000424 | 051055.7 | 54.77 | -2.81 | 347.6 | 541.5 | 13.8 | 2.6 | CALTHWAITE, CUMBRIA | 3+ | 18 | 9 | 133 | 0.09 | 0.3 | 0.7 | A*B | FELT CALTHWAITE... |
| 20000427 | 214408.9 | 61.49 | 3.82 | 709.7 | 1303.9 | 10.3 | 2.9 | NORTHERN NORTH SEA | | 15 | 66 | 191 | 0.37 | 2.3 | 1.9 | C*D | |
| 20000502 | 213811.2 | 52.55 | -0.81 | 480.7 | 295.4 | 15.3 | 2.1 | UPPINGHAM, LEICS | | 8 | 29 | 122 | 0.10 | 1.1 | 1.9 | B*B | 6KM SW OF UPPINGHAM |
| 20000505 | 045217.1 | 60.73 | 2.61 | 651.3 | 1214.3 | 16.8 | 3.6 | NORTHERN NORTH SEA | | 171 | 22 | 149 | 0.19 | 1.2 | 4.8 | B*D | |
| 20000520 | 161654.3 | 52.74 | -5.02 | 196.0 | 319.7 | 10.6 | 2.3 | IRISH SEA | | 11 | 29 | 215 | 0.09 | 1.0 | 0.8 | A*D | 20KM SW OF LLEYN PENIN |
| 20000622 | 143713.4 | 52.96 | -4.39 | 239.5 | 343.4 | 24.5 | 2.7 | LLEYN PENIN, GWYNEDD | 4+ | 11 | 3 | 85 | 0.05 | 0.4 | 1.0 | A*A | FELT LLANBERIS... |
| 20000630 | 115525.1 | 62.47 | 1.36 | 573.4 | 1403.8 | 18.4 | 2.8 | NORWEGIAN SEA | | 12 | 216 | 264 | 0.27 | 6.1 | 7.5 | D*D | |
| 20000710 | 090601.4 | 61.09 | 2.37 | 635.3 | 1252.8 | 22.5 | 2.2 | NORTHERN NORTH SEA | | 15 | 129 | 176 | 0.19 | 1.2 | 2.3 | B*D | |
| 20000808 | 024603.5 | 54.66 | -1.39 | 439.6 | 529.9 | 24.4 | 2.7 | MIDDLESBROUGH, CLEVELAND | | 5 | 10 | 163 | 0.09 | 3.0 | 4.1 | C*D | 8KM NW OF MIDDLESBROUGH |
| 20000809 | 191615.0 | 56.24 | -3.75 | 291.8 | 706.5 | 5.0 | 2.1 | BLACKFORD, TAYSIDE | 4+ | 8 | 15 | 104 | 0.05 | 0.4 | 0.7 | A*C | FELT BLACKFORD... |
| 20000811 | 062205.5 | 51.35 | -3.24 | 313.9 | 162.3 | 7.3 | 2.0 | BRISTOL CHANNEL | | 7 | 44 | 188 | 0.09 | 1.4 | 4.4 | B*D | |
| 20000812 | 142726.2 | 59.73 | 5.37 | 813.8 | 1116.7 | 15.0 | 4.5 | NORWEGIAN COAST | | 93 | 72 | 312 | 0.21 | | | D*D | |
| 20000824 | 074921.2 | 55.40 | -5.24 | 194.6 | 616.1 | 18.9 | 2.2 | ARRAN, STRATHCLYDE | | 8 | 23 | 136 | 0.09 | 0.8 | 2.5 | B*C | |
| 20000901 | 114837.7 | 59.24 | 5.73 | 840.4 | 1064.4 | 15.0 | 3.3 | NORWEGIAN COAST | | 8 | 375 | 333 | 0.18 | | | D*D | |
| 20000923 | 042345.8 | 52.28 | -1.61 | 426.6 | 264.8 | 14.4 | 4.2 | WARWICK, WARWICKSHIRE | 5 | 14 | 39 | 95 | 0.21 | 1.0 | 1.5 | B*C | FELT WARWICK... |
| 20001019 | 102724.8 | 57.42 | 6.88 | 932.2 | 871.1 | 15.0 | 3.9 | SKAGERRAK | | 19 | 221 | 273 | 0.35 | 7.0 | 8.2 | D*D | |
| 20001109 | 160816.9 | 62.26 | 2.24 | 620.0 | 1383.1 | 5.9 | 2.8 | NORTHERN NORTH SEA | | 12 | 165 | 254 | 0.31 | 7.6 | 8.0 | D*D | |
| 20001208 | 004805.9 | 60.16 | 4.64 | 767.9 | 1160.5 | 10.9 | 4.2 | NORWEGIAN COAST | 5+ | 24 | 35 | 90 | 0.54 | 2.4 | 2.7 | D*C | FELT BERGEN... |
| 20001208 | 055401.6 | 59.94 | 1.93 | 619.7 | 1124.1 | 10.3 | 4.6 | NORTHERN NORTH SEA | 3+ | 18 | 175 | 125 | 0.39 | 2.7 | 4.4 | C*D | FELT BRUCE FIELD |
| 20001213 | 051726.4 | 55.64 | -6.15 | 138.6 | 645.9 | 9.1 | 2.0 | ISLAY, INNER HEBRIDES | | 6 | 48 | 257 | 0.05 | 1.8 | 16.7 | C*D | |
| 20001219 | 093544.3 | 59.68 | 2.18 | 635.2 | 1095.3 | 14.6 | 2.2 | NORTHERN NORTH SEA | | 5 | 195 | 343 | 0.50 | | | D*D | |
| 20001221 | 235309.1 | 53.52 | 1.85 | 655.2 | 410.0 | 8.6 | 3.3 | SOUTHERN NORTH SEA | | 8 | 82 | 257 | 0.21 | 9.7 | 12.4 | D*D | 100KM N OF GT YARMOUTH |
| 20001228 | 004141.9 | 55.58 | -6.09 | 142.5 | 639.3 | 6.8 | 2.0 | ISLAY, INNER HEBRIDES | | 7 | 89 | 335 | 0.15 | 6.8 | 11.6 | D*D | 7KM OFFSHORE |
| 20001228 | 055533.5 | 60.03 | 1.79 | 611.0 | 1132.8 | 10.0 | 2.2 | NORTHERN NORTH SEA | | 6 | 165 | 317 | 0.46 | | | D*D | |
| 20001228 | 055658.0 | 59.93 | 1.80 | 612.3 | 1122.6 | 15.0 | 3.3 | NORTHERN NORTH SEA | | 10 | 168 | 170 | 0.36 | 6.0 | 9.1 | D*D | |
| 20001228 | 085955.4 | 55.67 | -6.13 | 140.6 | 649.2 | 11.1 | 2.2 | ISLAY, INNER HEBRIDES | | 5 | 89 | 334 | 0.05 | 2.9 | 2.0 | C*D | |
| 20001229 | 050157.3 | 59.66 | 1.71 | 608.9 | 1091.3 | 17.1 | 2.3 | NORTHERN NORTH SEA | | 7 | 170 | 180 | 0.14 | 3.5 | 4.2 | C*D | |

**ANNEX C**

**BRITISH GEOLOGICAL SURVEY**
**MURCHISON HOUSE**
**WEST MAINS ROAD**
**EDINBURGH EH9 3LA**

TEL: 0131 667 1000
TLX: 727343 SEISED G
FAX: 0131 667 1877 GSGG BGS
INTERNET: http://www.gsrg.nmh.ac.uk/.

TO:

| | | | |
|---|---|---|---|
| M THOMAS | - DETR | K KEIRLE | - WELSH ASSEMBLY |
| M WILSON | - SCOT H & H | H GULVANESSIAN | - BRE |
| P A MERRIMAN | - BNFL | J P McFARLANE | - BRITISH ENERGY |
| H TUR | - BNFL CAPEN | P FORD | - UKAEA |
| U MICHIE | - NIREX | P W WINTER | - AEA |
| J BETHELL | - BRITISH ENERGY | P SMITH | - HSE |
| C F ALLEN | - BNFL MAGNOX | V KARTHIGAYAN | - HSE OFFSHORE |
| W P ASPINALL | - AA | T EVANS | - BP |
| W B JACOB | - DIAS | S MONRO | - DYNAMIC EARTH |
| L J OLIVER | - S & S ENERGY | P BATES | - UKAEA |
| P M BRADFORD | - NII, BOOTLE | P McCORMACK | - PAISLEY OBSERVATORY |
| J E INKESTER | - NII, BOOTLE | R WATSON | - HISCOX |
| R WILLEMANN | - ISC | S BRACKELL | - BGS, LONDON INFO OFF |
| D J MALLARD | - CONSULTANT | R P SHAW | - BGS, KEYWORTH |
| C FLAWS | - SCOTTISH COAL | H J HEASON | - BGS PRESS OFFICE |
| C MCDONALD | - S & S ENERGY | M RAINES | - BGS, KEYWORTH |
| | | DIRECTOR | - BGS, KEYWORTH |

**FROM:** Bennett Simpson / Glen Ford
**DATE:** 23 September 2000
**TIME:** 08:00 UTC
**PAGES TO FOLLOW:** 3

## SEISMIC ALERT: WARWICK, WARWICKSHIRE 23 SEPTEMBER 2000 04:23 UTC 4.2 ML

BGS have received many reports, from the Police, the media, the Emergency Planning Officer and residents in Cheadle (85 km to the north), Gloucester (65 km to the south), Peterborough (95 kin to the east), Birmingham, Coventry. Warwick, Rugby, and Leamington Spa, of a felt event at 04:25 UTC this morning (23 September 2000). Felt reports describe "we were alarmed", "the bed moved", "the whole house shook", "we were woken from sleep" and "the whole building trembled". The BGS rapid-access networks detected an event at 04:23 UTC.

The following preliminary information is available for this earthquake:

| | | |
|---|---|---|
| DATE | : | 23 September 2000 |
| ORIGIN TIME | : | 04:23 45.8sUTC |
| LAT/LONG | : | 52.28º North / 1.61º West |
| GRID REF | : | 426.5 kmE / 265.0 kmN |
| DEPTH | : | 13.1 km |
| MAGNITUDE | : | 4.2 ML |
| INTENSITY | : | 5+ |
| LOCALITY | : | Warwick, Warickshire |

Historically, a similar earthquake occurred near Tewksbury, some 50 kin to the south west with a magnitude of 4.1 in 1768. More recently, a magnitude 3.0 earthquake was felt at Stratford-upon-Avon in May 1994, 17 km to the south west The largest earthquake within 100 km occurred at Bishops Castle near the Welsh border in April 1990, with a magnitude of 5. 1 (30 times the energy of the Warwick earthquake). It was felt over the whole of Wales, most of England and into Ireland and Scotland

A seismogram of the earthquake, as recorded on the BGS Hereford network, the strong motion record from Keyworth and a map of instrumental seismicity are attached.

**BRITISH GEOLOGICAL SURVEY**
**MURCHISON HOUSE**
**WEST MAINS ROAD**
**EDINBURGH EH9 3LA**

TEL: 0131 667 1000
TLX: 727343 SEISED G
FAX: 0131 667 1877 GSGG BGS
INTERNET: http://www.gsrg.nmh.ac.uk/.

TO:

| | | | |
|---|---|---|---|
| M THOMAS | - DETR | K KEIRLE | - WELSH ASSEMBLY |
| M WILSON | - SCOT H & H | H GULVANESSIAN | - BRE |
| P A MERRIMAN | - BNFL | J P McFARLANE | - BRITISH ENERGY |
| H TUR | - BNFL CAPEN | P FORD | - UKAEA |
| U MICHIE | - NIREX | P W WINTER | - AEA |
| J BETHELL | - BRITISH ENERGY | P SMITH | - HSE |
| C F ALLEN | - BNFL MAGNOX | V KARTHIGAYAN | - HSE OFFSHORE |
| W P ASPINALL | - AA | T EVANS | - BP |
| W B JACOB | - DIAS | S MONRO | - DYNAMIC EARTH |
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| P M BRADFORD | - NII, BOOTLE | P McCORMACK | - PAISLEY OBSERVATORY |
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| R WILLEMANN | - ISC | S BRACKELL | - BGS, LONDON INFO OFF |
| D J MALLARD | - CONSULTANT | R P SHAW | - BGS, KEYWORTH |
| C FLAWS | - SCOTTISH COAL | H J HEASON | - BGS PRESS OFFICE |
| C MCDONALD | - S & S ENERGY | M RAINES | - BGS, KEYWORTH |
| J DONALD | - NII, BOOTLE | DIRECTOR | - BGS, KEYWORTH |

**FROM:** Glen Ford
**DATE:** 21 February 2001
**TIME:** 13:00 UTC
**PAGES TO FOLLOW:** 0

## SEISMIC ALERT: SONIC BOOM NORTH YORKSHIRE & HUMBERSIDE COASTLINE 21 FEBRUARY 2001 11:20-11:40 UTC

BGS have received numerous reports that residents in Boulby, Whitby, Scarborough, Filey, Bridlington and Hornsea (approximately 80 km of coastline), felt an event (or events) between 11:20 and 11:40 UTC today. Felt reports describe "people running into the streets", "a loud bang like an explosion", "windows rattled' and "the whole building shook`. The nearest rapid-access networks were examined and no earthquakes were detected at the time. However, signals that could be consistent with a sonic origin were observed on the microphone at Leeds between 11:20 and 11:40 UTC.

The Ministry of Defence has confirmed that aircraft were operational at the time in the area.

# BGS STAFF WITH INPUT TO THE PROJECT

Mr Tom Alexander
Dr Brian Baptie
Ms Jacqueline Bott
Dr Chris W A Browitt
Mr Julian Bukits
Ms Freya Cromatry
Mr Daniel Dawes
Mr Peter S Day
Mr Simon Flower
Mr Glenn D Ford
Mr Charlie J Fyfe
Mr Davie D Galloway
Ms Helen Gordon
Mr Paul H O Henni
Dr David J Kerridge
Mr John Laughlin
Ms Margaret Milne
Dr Roger M W Musson
Mr Dave L Petrie
Mr David Scott
Mr Bennett A Simpson
Mr Ralph Southworth
Mr Dave A Stewart
Mr William A Velzian
Ms Alice B Walker

## GEOGRAPHICAL CO-ORDINATES OF SEISMOGRAPH STATIONS USED BY BGS :MARCH 2001

| Code | Name | Lat | Lon | GrE (Kms) | GrN (Kms) | Ht (m) | Yrs Open | Comp | Agency |
|---|---|---|---|---|---|---|---|---|---|
| **FAROES** | | | | | | | | | |
| FHV | HALDARSVIK | 62.2597 | -7.0984 | 135.46 | 1385.95 | 380 | 99- | 1R | BGS |
| FSD | SUDUROY | 61.5701 | -6.7884 | 145.86 | 1308.06 | 480 | 99- | 1R | BGS |
| FSV | SVINOY | 62.2598 | -6.3550 | 173.99 | 1383.14 | 430 | 99- | 1R | BGS |
| FTO | TORSHAVN | 62.0199 | -6.8274 | 147.51 | 1358.21 | 325 | 99- | 3R | BGS |
| FVA | VAGAR | 62.0575 | -7.3520 | 120.46 | 1364.55 | 430 | 99- | 1R | BGS |
| **SHETLAND** | | | | | | | | | |
| LRW | LERWICK | 60.1360 | -1.1779 | 445.66 | 1139.27 | 98 | 78- | 4R | BGS |
| LRWS | LERWICK (SM) | 60.1397 | -1.1831 | 445.37 | 1139.69 | 80 | 96- | 3 | BGS |
| SAN | SANDWICK | 60.0179 | -1.2392 | 442.41 | 1126.08 | 150 | 85- | 1 | BGS |
| WAL | WALLS | 60.2564 | -1.6173 | 421.18 | 1152.46 | 167 | 80- | 1 | BGS |
| YEL | YELL | 60.5509 | -1.0830 | 450.29 | 1185.55 | 203 | 79- | 1 | BGS |
| **ORKNEY** | | | | | | | | | |
| ORE | REAY | 58.5480 | -3.7622 | 297.45 | 963.52 | 100 | 95- | 4Rm | BGS |
| OTO | TONGUE | 58.4953 | -4.3939 | 260.49 | 958.79 | 338 | 95- | 1R | BGS |
| OHO | HOY | 58.8322 | -3.2465 | 328.05 | 994.48 | 172 | 95- | 1R | BGS |
| OWE | WESTRAY | 59.3180 | -3.0289 | 341.44 | 1048.36 | 87 | 95- | 1R | BGS |
| OST | STRONSAY | 59.0860 | -2.5516 | 368.39 | 1022.20 | 21 | 95- | 1R | BGS |
| OBR | BRABSTER | 58.6142 | -3.1626 | 332.47 | 970.13 | 89 | 95- | 1R | BGS |
| **MINCH** | | | | | | | | | |
| RRR | RUBHA REIDH | 57.8577 | -5.8067 | 174.19 | 891.68 | 61 | 95- | 4Rm | BGS |
| RSC | SCOURIE | 58.3485 | -5.1683 | 214.61 | 944.33 | 60 | 95- | 1R | BGS |
| RRH | RHENIGIDALE | 57.9197 | -6.6881 | 122.43 | 901.86 | 103 | 95- | 1R | BGS |
| RFO | FORSNAVAL | 58.2133 | -7.0052 | 106.10 | 935.83 | 195 | 95- | 1R | BGS |
| RTO | TOLSTA | 58.3778 | -6.2092 | 153.95 | 950.93 | 74 | 95- | 1R | BGS |
| RCR | CAPE WRATH | 58.6245 | -4.9987 | 225.90 | 974.58 | 100 | 95- | 1R | BGS |
| REB | EISG-BRACHAIDH | 58.1194 | -5.2802 | 206.82 | 919.16 | 100 | 95- | 1R | BGS |
| **MORAY** | | | | | | | | | |
| MCD | COLEBURN DISTIL | 57.5828 | -3.2541 | 325.02 | 855.42 | 293 | 81- | 4Rm | BGS |
| MDO | DOCHFOUR | 57.4409 | -4.3633 | 258.17 | 841.39 | 415 | 81- | 1R | BGS |
| MFI | FISHRIE | 57.6119 | -2.2956 | 382.34 | 858.00 | 232 | 88- | 1R | BGS |
| MLA | LATHERON | 58.3055 | -3.3627 | 320.15 | 935.98 | 188 | 81- | 1 | BGS |
| MME | MEIKLE CAIRN | 57.3149 | -2.9647 | 341.90 | 825.32 | 475 | 81- | 1 | BGS |
| MVH | ACHVAICH | 57.9250 | -4.1825 | 270.75 | 894.90 | 185 | 84- | 1 | BGS |
| **KYLE** | | | | | | | | | |
| KAC | ACHNASHELLACH | 57.4989 | -5.2988 | 202.36 | 850.19 | 206 | 83- | 1R | BGS |
| KAR | ARISAIG | 56.9188 | -5.8290 | 166.98 | 787.34 | 186 | 83- | 1 | BGS |
| KNR | NEVIS RANGE | 56.8219 | -4.9714 | 218.68 | 773.97 | 1147 | 91- | 1 | BGS |
| KPL | PLOCKTON | 57.3391 | -5.6527 | 180.21 | 833.50 | 13 | 86- | 4R | BGS |
| KSB | SHIEL BRIDGE | 57.2099 | -5.4214 | 193.40 | 818.40 | 417 | 83- | 1R | BGS |
| KSK | SCOVAL | 57.4659 | -6.7002 | 118.21 | 851.46 | 265 | 89- | 1R | BGS |
| **LOWNET** | | | | | | | | | |
| EAB | ABERFOYLE | 56.1887 | -4.3373 | 254.97 | 702.02 | 279 | 69- | 1R | BGS |
| EAU | AUCHINOON | 55.8454 | -3.4474 | 309.38 | 662.30 | 359 | 69- | 1R | BGS |
| EBH | BLACK HILL | 56.2476 | -3.5084 | 306.54 | 707.13 | 375 | 69- | 1R | BGS |
| EBL | BROAD LAW | 55.7723 | -3.0445 | 334.48 | 653.71 | 436 | 69- | 1R | BGS |
| EDI | EDINBURGH | 55.9233 | -3.1875 | 325.80 | 670.66 | 125 | 69- | 4R | BGS |
| EDR | DRUMTOCHTY | 56.9190 | -2.5393 | 367.17 | 780.97 | 401 | 89- | 1R | BGS |
| EDU | DUNDEE | 56.5477 | -3.0110 | 337.85 | 739.97 | 421 | 69- | 1R | BGS |
| ELO | LOGIEALMOND | 56.4703 | -3.7112 | 294.59 | 732.21 | 523 | 69- | 1R | BGS |
| ESY | STONEYPATH | 55.9175 | -2.6141 | 361.62 | 669.55 | 337 | 81- | 1R | BGS |

# GEOGRAPHICAL CO-ORDINATES OF SEISMOGRAPH STATIONS USED BY BGS :MARCH 2001

| Code | Name | Lat | Lon | GrE (Kms) | GrN (Kms) | Ht (m) | Yrs Open | Comp | Agency |
|---|---|---|---|---|---|---|---|---|---|
| **PAISLEY** | | | | | | | | | |
| PCA | CARROT | 55.7007 | -4.2550 | 258.30 | 647.55 | 302 | 83- | 1 | BGS |
| PCO | CORRIE | 55.9880 | -4.1002 | 269.00 | 679.21 | 267 | 83- | 1 | BGS |
| PGB | GLENIFFERBRAES | 55.8115 | -4.4837 | 244.38 | 660.37 | 199 | 84- | 3 | BGS |
| PMS | MUIRSHIEL | 55.8459 | -4.7452 | 228.15 | 664.82 | 351 | 83- | 1 | BGS |
| POB | OBSERVATORY | 55.8458 | -4.4299 | 247.88 | 664.06 | 34 | 92- | 1 | BGS |
| **ESKDALEMUIR** | | | | | | | | | |
| ESK | ESKDALEMUIR | 55.3165 | -3.2052 | 323.52 | 603.16 | 261 | 65- | 4R | BGS |
| ECK | CAULDKAINE HILL | 55.1810 | -3.1292 | 328.10 | 588.00 | 351 | 81- | 1R | BGS |
| XAL | ALLENDALE | 54.8617 | -2.2147 | 386.22 | 551.91 | 458 | 83- | 1R | BGS |
| XSO | SOURHOPE | 55.4924 | -2.2510 | 384.14 | 622.10 | 516 | 83- | 1R | BGS |
| **GALLOWAY AND N IRELAND** | | | | | | | | | |
| GAL | GALLOWAY | 54.8664 | -4.7114 | 226.02 | 555.78 | 117 | 89- | 4m | BGS |
| GCL | CUSHENDALL | 55.0783 | -6.1264 | 136.66 | 583.77 | 278 | 89- | 1R | BGS |
| GMK | MULL OF KINTYRE | 55.3458 | -5.5934 | 172.19 | 611.64 | 164 | 89- | 1R | BGS |
| GMM | MTNS OF MOURNE | 54.2377 | -5.9498 | 142.66 | 489.67 | 155 | 89- | 1R | BGS |
| **BORDERS** | | | | | | | | | |
| BBH | BRUNTSHEIL | 55.1333 | -2.9299 | 340.72 | 582.50 | 216 | 92- | 1 | BGS |
| BNA | NEW ABBEY | 54.9658 | -3.6242 | 296.03 | 564.68 | 28 | 92- | 1 | BGS |
| BHH | HOWATS HILL | 55.0931 | -3.2181 | 322.27 | 578.31 | 216 | 92- | 3 | BGS |
| BTA | TALKIN | 54.9057 | -2.6844 | 356.12 | 557.00 | 279 | 92- | 3 | BGS |
| BDL | DOBCROSS HALL | 54.8030 | -2.9385 | 339.68 | 545.76 | 157 | 92- | 1 | BGS |
| BWH | WARDLAW | 55.1758 | -3.6549 | 294.62 | 588.09 | 269 | 92- | 1 | BGS |
| BBO | BOTHEL ** | 54.7367 | -3.2464 | 319.76 | 538.69 | 209 | 92- | 3 | BGS |
| BCM | CHAPELCROSS | 55.0151 | -3.2212 | 321.92 | 569.64 | 78 | 92- | m | BGS |
| BCC | CHAPELCROSS | 55.0153 | -3.2201 | 321.99 | 569.66 | 138 | 92- | 1 | BGS |
| **CUMBRIA** | | | | | | | | | |
| CKE | KESWICK | 54.5877 | -3.1059 | 328.54 | 521.96 | 304 | 92- | 1 | BGS |
| CSF | SCAFELL | 54.4478 | -3.2430 | 319.41 | 506.55 | 540 | 92- | 1 | BGS |
| CDU | DUNNERDALE | 54.3362 | -3.1952 | 322.30 | 494.08 | 355 | 92- | 1 | BGS |
| CSM | SELLAFIELD | 54.4183 | -3.4913 | 303.24 | 503.58 | 50 | 92- | m | BGS |
| LMI | MILLOM * | 54.2206 | -3.3070 | 314.79 | 481.35 | 129 | 89- | 3R | BGS |
| GIM | ISLE OF MAN(N)* | 54.2923 | -4.4672 | 239.44 | 491.35 | 346 | 89- | 3R | BGS |
| GCD | CASTLE DOUGLAS* | 54.8630 | -3.9403 | 275.48 | 553.76 | 184 | 89- | 1R | BGS |
| XDE | DENT * | 54.5056 | -3.4902 | 303.52 | 513.29 | 301 | 83- | 1R | BGS |
| **LEEDS** | | | | | | | | | |
| HPK | HAVERAH PARK | 53.9581 | -1.6241 | 424.66 | 451.42 | 233 | 78- | 3R | BGS |
| LCP | CASSOP | 54.7370 | -1.4744 | 433.84 | 538.14 | 185 | 91- | 1 | BGS |
| LWH | WHINNY NAB | 54.3338 | -0.6717 | 486.36 | 493.97 | 277 | 91- | 1R | BGS |
| LRN | RICHMOND | 54.4165 | -1.8007 | 412.93 | 502.37 | 313 | 91- | 1R | BGS |
| LMK | MARKET RASEN | 53.4569 | -0.3260 | 511.14 | 396.90 | 146 | 91- | 1 | BGS |
| LHO | HOLMFIRTH | 53.5453 | -1.8548 | 409.62 | 405.44 | 462 | 91- | 1 | BGS |
| LDU | LEEDS | 53.8058 | -1.5540 | 429.37 | 434.51 | 74 | 83- | 2Rm | BGS |

## GEOGRAPHICAL CO-ORDINATES OF SEISMOGRAPH STATIONS USED BY BGS :MARCH 2001

| Code | Name | Lat | Lon | GrE (Kms) | GrN (Kms) | Ht (m) | Yrs Open | Comp | Agency |
|---|---|---|---|---|---|---|---|---|---|
| **NORTH WALES** | | | | | | | | | |
| WCB | CHURCH BAY | 53.3782 | -4.5467 | 230.62 | 389.87 | 139 | 85- | 4m | BGS |
| WFB | FAIRBOURNE | 52.6831 | -4.0383 | 262.23 | 311.48 | 316 | 85- | 1R | BGS |
| WIM | ISLE OF MAN (S) | 54.1475 | -4.6738 | 225.39 | 475.73 | 386 | 85- | 1R | BGS |
| WLF | LLYNFAES | 53.2894 | -4.3966 | 240.27 | 379.65 | 58 | 85- | 1 | BGS |
| WME | MYNDD EILIAN | 53.3969 | -4.3032 | 246.88 | 391.40 | 129 | 85- | 1R | BGS |
| WPM | PENMAENMAWR | 53.2581 | -3.9048 | 272.95 | 375.18 | 353 | 85- | 1 | BGS |
| YRC | RHOSCOLYN | 53.2508 | -4.5753 | 228.21 | 375.77 | 22 | 84- | 1R | BGS |
| YRE | YR EIFL | 52.9811 | -4.4254 | 237.19 | 345.43 | 193 | 84- | 1R | BGS |
| YLL | LLANBERIS | 53.1402 | -4.1704 | 254.84 | 362.57 | 159 | 84- | 1R | BGS |
| YRH | RHIW | 52.8336 | -4.6288 | 222.94 | 329.51 | 286 | 84- | 1R | BGS |
| **KEYWORTH** | | | | | | | | | |
| CWF | CHARNWOODFST | 52.7385 | -1.3076 | 446.74 | 315.91 | 203 | 75- | 3R | BGS |
| KBI | BIRLEY GRANGE | 53.2543 | -1.5279 | 431.49 | 373.17 | 272 | 88- | 1 | BGS |
| KEY | KEYWORTH | 52.8779 | -1.0757 | 462.20 | 331.59 | 59 | 88- | 1 | BGS |
| KEY2 | KEYWORTH (SM) | 52.8790 | -1.0770 | 462.13 | 331.73 | 76 | 97- | 3 | BGS |
| KSY | SYSTON | 52.9642 | -0.5872 | 494.88 | 341.73 | 121 | 88- | 1R | BGS |
| KTG | TILBROOK GRANGE | 52.3264 | -0.4019 | 508.90 | 271.06 | 83 | 88- | 1 | BGS |
| KUF | UFFORD | 52.6170 | -0.3907 | 508.94 | 303.39 | 38 | 88- | 1R | BGS |
| KWE | WEAVER FARM | 53.0164 | -1.8412 | 410.65 | 346.61 | 328 | 88- | 1R | BGS |
| **EAST ANGLIA** | | | | | | | | | |
| ABA | BACONSTHORPE | 52.8884 | 1.1453 | 611.58 | 337.00 | 74 | 82- | 1 | BGS |
| AEA | E.ANGLIA UNIV. | 52.6208 | 1.2403 | 619.30 | 307.53 | 45 | 84- | m | BGS |
| APA | PACKWAY | 52.3006 | 1.4782 | 637.12 | 272.68 | 58 | 84- | 1 | BGS |
| AWH | WHINBURGH | 52.6297 | 0.9507 | 599.67 | 307.68 | 64 | 80- | 1R | BGS |
| AWI | WITTON | 52.8319 | 1.4471 | 632.17 | 331.65 | 46 | 83- | 1 | BGS |
| AEU | E.ANGLIA | 52.6202 | 1.2347 | 618.93 | 307.45 | 28 | 94- | 4 | BGS |
| **HEREFORD** | | | | | | | | | |
| SBD | BRYN DU | 52.9055 | -3.2585 | 315.37 | 335.01 | 489 | 80- | 1 | BGS |
| MCH | MICHAELCHURCH | 51.9974 | -2.9983 | 331.47 | 233.74 | 219 | 78- | 4 | BGS |
| HAE | ALDERS END | 52.0368 | -2.5434 | 362.73 | 237.79 | 260 | 82- | 1R | BGS |
| HCG | CRAIG GOCH | 52.3231 | -3.6570 | 287.08 | 270.78 | 533 | 80- | 1R | BGS |
| HGH | GRAY HILL | 51.6379 | -2.8057 | 344.25 | 193.59 | 223 | 80- | 1R | BGS |
| HLM | LONG MYND | 52.5184 | -2.8807 | 340.25 | 291.57 | 429 | 84- | 1 | BGS |
| HTR | TREWERN HILL | 52.0785 | -3.2679 | 313.12 | 243.04 | 337 | 82- | 1R | BGS |
| SSP | STONEY POUND | 52.4177 | -3.1119 | 324.39 | 280.59 | 428 | 90- | 3 | BGS |
| HBL2 | BONNYLANDS | 52.0508 | -3.0384 | 328.80 | 239.71 | 437 | 91- | 1R | BGS |
| **SWINDON** | | | | | | | | | |
| SWN | SWINDON | 51.5131 | -1.8004 | 413.85 | 179.42 | 192 | 93- | 4 | BGS |
| SMD | MENDIPS | 51.3083 | -2.7170 | 350.03 | 156.88 | 310 | 93- | 1 | BGS |
| SSW | STOW-ON-WOLD | 51.9667 | -1.8499 | 410.31 | 229.86 | 291 | 93- | 1 | BGS |
| SWK | WARMINSTER | 51.1483 | -2.2471 | 382.72 | 138.87 | 266 | 93- | 1 | BGS |
| SFH | HASELMERE | 51.0604 | -0.6912 | 491.71 | 129.88 | 260 | 93- | 1 | BGS |
| SIW | ISLE OF WIGHT | 50.6711 | -1.3747 | 444.18 | 85.97 | 162 | 93- | 1 | BGS |
| SKP | KOPHILL | 51.7218 | -0.8096 | 482.22 | 203.29 | 212 | 93- | 1 | BGS |

## GEOGRAPHICAL CO-ORDINATES OF SEISMOGRAPH STATIONS USED BY BGS :MARCH 2001

| Code | Name | Lat | Lon | GrE (Kms) | GrN (Kms) | Ht (m) | Yrs Open | Comp | Agency |
|---|---|---|---|---|---|---|---|---|---|
| **SOUTH EAST ENGLAND** | | | | | | | | | |
| TFO | FOLKESTONE | 51.1135 | 1.1409 | 619.81 | 139.66 | 202 | 89- | 4m | BGS |
| TEB | EASTBOURNE | 50.8187 | 0.1457 | 551.13 | 104.39 | 68 | 89- | 1R | BGS |
| TSA | SEVENOAKS | 51.2426 | 0.1561 | 550.48 | 151.53 | 177 | 89- | 1 | BGS |
| TBW | BRENTWOOD | 51.6549 | 0.2913 | 558.48 | 197.66 | 89 | 89- | 1R | BGS |
| TCR | COLCHESTER | 51.8347 | 0.9212 | 601.24 | 219.20 | 45 | 89- | 1R | BGS |
| **CORNWALL** | | | | | | | | | |
| CMA | MANACCAN | 50.0821 | -5.1274 | 176.29 | 24.98 | 42 | 93- | 1 | BGS |
| CCA | CARNMENELLIS | 50.1866 | -5.2277 | 169.62 | 36.90 | 210 | 81- | 1 | BGS |
| CBW | BUDOCK WATER | 50.1482 | -5.1144 | 177.53 | 32.29 | 94 | 81- | 1 | BGS |
| CCO | CONSTANTINE | 50.1357 | -5.1957 | 171.66 | 31.14 | 168 | 81- | 1 | BGS |
| CGH | GOONHILLY | 50.0507 | -5.1649 | 173.46 | 21.60 | 97 | 81- | 1 | BGS |
| CPZ | PENZANCE | 50.1566 | -5.5828 | 144.12 | 34.72 | 199 | 81- | 1R | BGS |
| CR2 | ROSEMANOWES 2 | 50.1667 | -5.1687 | 173.74 | 34.51 | 143 | 81- | 3 | BGS |
| CRQ | ROSEMANOWES | 50.1672 | -5.1726 | 173.46 | 34.57 | 156 | 81- | 4R | BGS |
| CSA | ST AUSTELL | 50.3527 | -4.8919 | 194.30 | 54.38 | 112 | 81- | 1 | BGS |
| CST | STITHIANS | 50.1952 | -5.1635 | 174.24 | 37.66 | 141 | 81- | 1 | BGS |
| CGW | GWEEK | 50.1006 | -5.2228 | 169.56 | 27.32 | 9 | 93- | 1 | BGS |
| **DEVON** | | | | | | | | | |
| DCO | COMBE FARM | 50.3201 | -3.8721 | 266.74 | 48.43 | 117 | 82- | 1R | BGS |
| DYA | YADSWORTHY | 50.4353 | -3.9310 | 262.88 | 61.34 | 292 | 82- | 3R | BGS |
| HTL | HARTLAND | 50.9943 | -4.4849 | 225.64 | 124.66 | 86 | 81- | 4Rm | BGS |
| HSA | SWANSEA | 51.7500 | -4.1532 | 251.38 | 207.94 | 293 | 87- | 1R | BGS |
| HPE | PEMBROKE | 51.9372 | -4.7746 | 209.29 | 230.21 | 349 | 90- | 1R | BGS |
| HEX | EXMOOR | 51.0664 | -3.8026 | 273.71 | 131.28 | 230 | 91- | 1R | BGS |
| **JERSEY** | | | | | | | | | |
| JQE | QUEENS EAST | 49.2000 | -2.0383 | | | 58 | 91- | 1 | BGS |
| JLP | LES PLATONS | 49.2486 | -2.1039 | | | 129 | 81- | 1R | BGS |
| JRS | MAISON ST LOUIS | 49.1922 | -2.0922 | | | 56 | 81- | 4R | BGS |
| JSA | ST AUBINS | 49.1878 | -2.1717 | | | 39 | 81- | 1R | BGS |
| JVM | VALLE D.L.MARE | 49.2169 | -2.2067 | | | 64 | 81- | 1R | BGS |

Notes

1. The UK seismograph network is divided into a number of sub-networks, named Cornwall, Devon etc, within which data are transmitted, principally by radio, from each seismometer station to a central recorder where it is registered against a common, accurate time standard.

2. From left to right the column headers stand for Latitude, Longitude, Easting, Northing, Height, Year station opened, number of seismometers at the station (Comp) and the agency operating the station (in this list they are all BGS).

3. Qualifying symbols indicate the following:

R in Comp column : station details have been registered with international agencies for data exchange.

m in Comp column : low frequency microphone also deployed.

* after Name : station removed from original network to be transmitted to a new centre.

** after Name : station transmitting to both the Cumbria and Borders network centres.

# PROJECT PUBLICATIONS ANNEX F

**BGS Seismology reports**

| | |
|---|---|
| WL/00/03 | Walker, A.B. UK Earthquake monitoring 1999/00, BGS Seismic Monitoring and Information Service, Eleventh Annual Report. June 2000. |
| IR/00/15 | Musson, R.M.W., 2000. An illustrative seismic hazard and risk case: Nagoya, Japan. June 2000. |
| IR/01/28 | Simpson, B.A (ed), Ford, G.D., and Galloway, D.D. Bulletin of British Earthquakes 2000. March 2001 |

In addition, 9 confidential reports were prepared and bulletins of seismic activity were produced monthly, up to 6 weeks in arrears, for the Customer Group sponsoring the project.

**External Publications**

Amorese, D., Walker, A.B., Lagarde, J.-L., Santoire, J.-P., Volant, P., Font, M. and Lecornu, M., 2000. New seismotectonic data from an iuntraplate region:focal mechanisms in the Armorican Massif (northwestern France). *Geophys. J. Int*. (2000) **143**, 837-846

Baptie, B., Luckett, R. and Neuberg, J. Variability of tremor episodes on Montserrat, in The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. Memoir of the Geological Society of London. *In press*.

Baptie, B. The BGS seismic monitoring network. In proceedings of Geoscience 2000, University of Manchester, 2000.

Baptie, B. Modelling volcanic tremor associated with vulcanian explosions on Monserrat. In proceedings of Geoscience 2000, University of Manchester, 2000.

Baptie, B. The relationship between volcanic tremor and cyclic gas exhalations at Soufrière Hills Volcano, Montserrat. In proceedings of Seismic phenomena associated with volcanic activity, European Seismological Commission, annual workshop, Azores.

Bott, J.D.J. 2000, Upper crustal P- and S-wave velocity structure of central and western Scotland using a joint hypocenter velocity inversion, (abs), Book of Abstracts and Papers, XXVII General Assembly of the European Seismological Comission (ESC), p. 44.

Bott, J.D.J., Wong, I.G., Ake, J., Steele Weir, S., 2000, Upper crustal velocities for the Central Front Range, Colorado, using joint hypocenter velocity inversion, (abs), EOS, Transactions of the American Geophysical Union, v. 81 p. F1197.

Bott, J.D.J. (2001 in press), The magnitude 4.2 Warwick earthquake of 23 September 2000, Publication of the Warwick Conservation Group, 5 p.

Dawson, A.G., Musson, R.M.W., I.D.L. Foster and D. Brunsden, 2000. Abnormal historic sea-surface fluctuations, SW England, Marine Geology, vol 170, pp 59-68.

Firth, C.R. and Stewart, I.S., 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. Quaternary Science Reviews, Vol. 19 (14-15) (2000) pp. 1469-1493

Galloway, D.D. and Simpson, B., 2001. A summary of earthquakes in 2000. The Society for Earthquake and Civil Engineering Dynamics (SECED) Newsletter. Vol 15 No 1, March 2001.

Jiménez, M.J., Giardini, D., Grünthal, G., Erdik, M., Garcia-Fernández, M., Lapajne, J., Makropoulos, K., Musson, R.M.W., Papaioannou, C., Riad, S., Sellami, S., Shapira, A., Slejko, D. and Eck, T. van, 2000. Unified seismic hazard modelling throughout the Mediterranean region, Abstracts and papers of the XXVII Gen. Ass. of the ESC, 10-15 Sep 2000, Lisbon, pp 93,96.

Kerridge, D. and Flower, S., 2000. Recording and delivering seismic and geomagnetic data. BGS Earthwise Issue 16 pp. 14-15

Luckett, R., Baptie, B. and Neuberg J. The relationship between degassing and rockfall signals at Soufriere Hill Volcano Montserrat, in The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999. Memoir of the Geological Society of London. *In press*.

Musson, R.M.W., 2000. Evaluation of seismic hazard source models, in Lapajne, J. and Vidrih, R. (eds), Seismicity modelling in seismic hazard mapping, Slovenian Geophysical Survey, Ljubljana, pp 53-66.

Musson, R.M.W., 2000. On the transition from probabilistic seismic hazard to probabilistic seismic risk, Abstracts of the NATO Advanced Research Seminar, "Integration of earth sciences research on the 1999 Turkish and Greek earthquakes and needs for future co-operative research", Istanbul 14-17 May 2000, p122.

Musson, R.M.W., 2000. The historical seismicity of places with no earthquakes, Abstracts and papers of the XXVII Gen. Ass. of the ESC, 10-15 Sep 2000, Lisbon, p116.

Musson, R.M.W., 2000. The seismicity of Cornwall and Devon, Geoscience in South-West England, vol 10, pp 34-36.

Musson, R.M.W., 2000. Intensity-based seismic risk assessment, Soil Dynamics and earthquake Engineering, vol 20, pp 353-360.

Neuberg, J., Luckett, R., Baptie, B. and Olsen K. Models of tremor and low-frequency earthquake swarms on Montserrat. Journal of Volcanology and Geothermal Research, 101,83-104.

Stewart, I.S., Sauber, J., and Rose, J., 2000. Glacio-seismotectonics: ice sheets, crustal deformation and seismicity. Quaternary Science Reviews, Vol. 19 (14-15) (2000) pp. 1367-1389

**UK EARTHQUAKE MONITORING 1999/00 BGS SEISMIC MONITORING AND INFORMATION SERVICE: ELEVENTH ANNUAL REPORT**

**A B Walker**

The aims of the BGS 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 the Environment, Transport and the Regions (DETR) with major financial input from the Natural Environment Research Council (NERC). This Customer Group is listed in Annex A.

In the eleventh year of the project (April 1999 to March 2000), a five station network in the Faroe islands, one additional strong-motion instrument and three large capacity data storage disks were installed. Five strong-motion records were captured from three of the eighteen sites now equipped with these instruments. Some gaps still remain in station coverage; notably in Northern Ireland. Other areas with site-specific networks, in Jersey, northern Scotland, Outer Hebrides and the Orkney Islands, remain vulnerable to closure owing to their dependency on funds from the commissioning bodies.

Some 147 earthquakes were located by the monitoring network in 1999, with 27 of them having magnitudes of 2.0 ML or greater and 33 were reported as felt. The largest felt earthquake in the reporting year (April 1999 to March 2000), with a magnitude of 3.6 ML, occurred near Sennybridge, Powys on 25 October 1999. A macroseismic survey was conducted and around 270 replies were received, giving a maximum intensity of 5 EMS (European Macroseismic Scale, Annex H). The largest offshore earthquake occurred near the Norwegian coast on 29 May. It had a magnitude of 4.1 ML and was located approximately 360 km northeast of the Shetland Islands. It was felt on the Norwegian coast over an area of approximately 300 $km^2$. In addition to earthquakes, BGS frequently receives reports of seismic events, felt and heard, which on investigation prove to be sonic booms, or in coalfield areas, where much of the activity is probably induced by mining, or spurious. During the reporting period, data on one controlled explosion and 6 sonic events were processed and reported upon following public concern or media attention.

All significant felt events and some others are reported rapidly to the Customer Group through 'seismic alerts' sent by fax and are subsequently followed up in more detail. The alerts are also available on the Internet (www.gsrg.nmh.ac.uk). Monthly seismic bulletins were issued 6 weeks in arrears and, following revision, were compiled into an annual bulletin (Walker, 2000). In all these reporting areas, scheduled targets have been met or surpassed.

The potential of the network's data links and computing capabilities to provide an environmental monitoring capacity has been further developed with the installation of a full demonstration system at Eskdalemuir Observatory, recording 20 environmental parameters which are accessible on-line through an internet connection.

**AN ILLUSTRATIVE SEISMIC HAZARD AND RISK CASE: NAGOYA, JAPAN**

**R M W Musson**

This report gives an example of the use of probabilistic seismic risk assessment, based on Monte Carlo simulation and intensity distribution. It presents a simple study of seismic hazard and risk for the city of Nagoya, Japan. It is intended to show the sorts of calculations that can be made on the probability of earthquake damage using the concept of earthquake intensity. Earthquake risk studies are often based around the prediction of peak ground acceleration (pga) values as a function of earthquake magnitude and distance, and then the estimation of probable damage distribution as a function of pga and building vulnerability. The problem with this is that damage correlates very poorly with pga; this has been known for as long as pga values have been measured. The use of intensity as a measure of earthquake shaking avoids this problem. Intensity is measured directly from damage, and thus an intensity attenuation function effectively allows one to reconstruct damage distributions, with appropriate modifications for local factors such as soil conditions and directivity. The difficulty with this approach in the past has been the rigid nature of early intensity scales such as the so-called Modified Mercalli scale (actually nothing to do with Mercalli). Modern scales such as the European

Macroseismic Scale (EMS-98) apply a probabilistic approach to damage distributions and an adaptable scheme for handling building vulnerability, and are thus ideally suited for risk estimation applications. In this study, generic seismic risk curves are produced for the city of Nagoya that allow one to estimate the probability of different degrees of loss to buildings of different vulnerability classes. Thus if one were interested in a particular collection of (for example) reinforced concrete office buildings with a known total value, by consulting the appropriate curve one could estimate the probability of any actual loss figure to those buildings.

**BULLETIN OF BRITISH EARTHQUAKES 2000**

**B Simpson (editor)**

There have been 156 earthquakes located by the monitoring network during the year, with 35 of them having magnitudes of 2.0 ML or greater. Of these, 8 are known to have been felt, together with a further 9 smaller ones, bringing the total to 17 felt earthquakes in 2000.

The largest onshore earthquake, with a magnitude of 4.2 ML, occurred near Warwick on 23 September (Appendix A1). It was felt up to 150 km away and over an area of 14,900 $km^2$ at isoseismal 3 EMS. A macroseismic survey conducted after the event yielded over 2,500 replies and the resulting map of felt effects is shown in Appendix A1. The highest observed intensity was 5 EMS at Warwick, where in a number of cases, objects such as ornaments, pictures or toys fell or were displaced. In a few cases, heavy objects were also said to have been displaced, including two washing machines, a cooker, a microwave and a sofa. The nearest 3-component strong motion instrument to record the earthquake was 76 km distant and accelerations of 17.3, 16.6 and 20.8 $mms^{-2}$ were recorded for the vertical, NS and EW components, respectively. The focal mechanism indicates almost pure normal faulting on a NW-SE oriented plane, dipping either to the NE or to the SW.

The largest offshore earthquake occurred in the northern North Sea on 8 December. It had a magnitude of 4.6 ML and was located approximately 175 km east of the Shetland Islands. It was felt on a nearby oil platform in the Bruce field (20 km SW of the epicentre). One staff member reported that "the size of the movement was similar to that experienced in storm conditions although the sea state wasn't more than a few metres at the time". Using a standard attenuation formula, it is estimated that a ground acceleration of 0.04g might have been experienced at this range; enough to be felt strongly on land. Platform dynamics may have amplified the effect at deck level.

An earthquake, with a magnitude of 4.2 ML, was located on the Norwegian Coast also on 8 December. It was felt with intensities of 5 EMS around Bergen, Norway. A further 20 events occurred in the North Sea and surrounding waters during the year, with magnitudes ranging between 1.0 and 4.5 ML, and were located using both the BGS and Norwegian networks.

Near Lochgilphead, Strathclyde, an earthquake, with a magnitude of 2.7 ML, occurred on 12 February. It was felt in Kames, Lochgilphead and Achahoish where residents described "tins fell off the shelf", "the house was shaking" and "was woken up from sleep", indicating an intensity of at least 4 EMS. Although the general area is seismically active, this is the largest event since the magnitude 3.5 ML Lochgilphead earthquake in 1972, some 20 km to the northeast, which was also felt with intensities of at least 4 EMS.

Near Doune, Central Scotland, an earthquake with a magnitude of 2.3 ML occurred on 20 February. It was felt in Doune and Dunblane where residents described "windows and radiators rattled", indicating an intensity of at least 3 EMS. This is an area which has experienced a number of earthquakes in the past. In particular, in 1997, a swarm of ten earthquakes occurred with magnitudes ranging between 0.9 and 2.7 ML. The two largest of these were felt with intensities of at least 4 EMS.

Two events occurred near Calthwaite, Cumbria with magnitudes of 0.5 and 2.6 ML. The latter occurred on 24 April (Appendix A2) and felt reports described "the whole house shook" and "the windows rattled", indicating an intensity of at least 3 EMS. The nearest 3-component strong motion instrument to record the earthquake was 38 km distant and accelerations of 1.3, 7.2 and 1.4 $mms^{-2}$ were recorded for the vertical, NS and EW components, respectively. A focal mechanism for the larger event was calculated and shows dominantly normal faulting with a minor component of strike-slip. The nodal planes strike NNW-SSE.

In North Wales, six events with magnitudes ranging between 0.0 to 2.7 ML, were located 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 magnitude 2.7 ML event occurred on 22 June (Appendix A3) and felt reports were received via the media, the Police and residents in Dinorwic, Maentwrog, Llanberis and Caernarvon, North Wales. These reports described "the whole house shook" and "felt a shudder", indicating an intensity of at least 4 EMS. This is the largest event in the Lleyn Peninsula area since the magnitude 2.7 ML earthquake on 15 April 1986, which was felt with intensities of 2 EMS in Pwllheli and Porthmadog. The calculated focal mechanism shows dominantly strike-slip faulting with a varying component of dip-slip. The nodal planes strike WNW-ESE and N-S. This is in reasonable agreement with the calculated focal mechanism for the 1984 earthquake. The P and T-axes are consistent with the regional stress direction for the UK.

Near Middlesbrough, Cleveland, an earthquake with a magnitude of 2.7 ML occurred on 8 August. Earthquakes of this size are usually felt when they occur onshore but enquiries to local Police stations and post offices revealed that no felt reports were received. The depth (24.4 km) may have contributed to the lack of felt effects. This is an area that has experienced little seismicity in both the historical and instrumental periods, with only two events located since 1970 within 10 km of this event.

Fourteen earthquakes were detected in the Blackford area of Tayside during the year 2000, with magnitudes ranging between 0.4 and 2.1 ML. The largest occurred on 9 August and was felt in the Blackford and Glendevon areas of Tayside, where intensities reached at least 3 EMS. Felt reports described "the furniture moved" and "the building shook". 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 and 3 in 1999. In the same general area on 19 February 1979, a magnitude 3.2 ML Ochil Hills earthquake was felt with a maximum intensity of 5 EMS.

Seven events, with magnitudes ranging between 0.7 and 1.8 ML, occurred near Dumfries, Dumfries and Galloway. Two of these events with magnitudes of 1.2 and 1.8 ML were felt by local residents in the Tinwald area of Dumfries and Galloway, where intensities reached at least 3 EMS.

Near Dollar, an earthquake with a magnitude of 1.1 ML, occurred on 25 September. Felt reports were received from the village of Rumbling Bridge, where intensities reached at least 3 EMS. Felt reports described "a rumbling beneath the feet", "felt a thud" and "the whole house shook". This is the first felt event in the Dollar area, since the magnitude 1.0 ML earthquake, on 25 August 1999, which was felt in the Forest Mill area, with intensities of at least 2 EMS.

An earthquake, with a magnitude of 1.4 ML, occurred near Mold, Clwyd on 3 November. Felt reports were received via the North Wales Environment Agency, Flintshire County Council and residents of Eryrys and Nercwys. Felt reports described "heard a tremendous bang", "like a boulder hitting the side of the house" and "ornamental plates on the shelves rattled", indicating an intensity of at least 4 EMS. This is the first felt event within 30 km of Mold, since the magnitude 4.5 ML Widnes earthquake, on 3 November 1976, which was felt with intensities of 4 EMS.

The coalfield areas of Yorkshire, Staffordshire, Mid Glamorgan, Northumberland and Nottinghamshire continued to experience shallow earthquake activity that is believed to be mining induced. Some 13 coalfield events, with magnitudes ranging between 0.8 and 1.9 ML, were detected during the year. Three of these were reported felt by local residents. The largest coalfield event (1.9 ML), occurred near Doncaster, South Yorkshire on 4 August. Felt reports were received via Yorkshire Television and residents of the Woodlands area of Doncaster, where intensities reached at least 5 EMS. Felt reports described "the walls shook" and "the whole street ran outside". This is an area that has experienced similar events in the past.

**NEW SEISMOTECTONIC DATA FROM AN INTRAPLATE REGION:FOCAL MECHANISMS IN THE AMORICAN MASSIF (NORTH-WESTERN FRANCE)**

**D Amorese, A B Walker, J-L Lagarde, J-P Santoire, P Volant, M Font and M Lecornu**

Focal mechanism solutions are determined for 11 small intraplate earthquakes that occurred between 1990 and 1998 in Normandy and the Channel Islands. These mechanisms are obtained from the *P*-wave first-motion polarities recorded by the stations from local and regional seismic networks. The accuracy of each hypocentral location is closely examined and the quality of each fault plane solution is discussed by considering the influence of the velocity structure. The predominant feature of the computed focal mechanisms is the relatively widespread near-horizontal NE-SW T-axis orientation. Horizontal P-axes strike roughly NW-SE. Mechanism solutions for the earthquakes in the Avranches region show left-lateral strike slip on a NNW-SSE fault Zone.

For the overall region, it seems that nodal planes of normal faulting solutions trend NW-SE or WNW-ESE, whereas those of thrust faulting solutions trend NE-SW. This is an agreement with the general regional stress pattern. The NE-SW normal fault plane solution of the 1990 Jersey event is unique because it is not consistent with the regional style of faulting.

## VARIABILITY OF TREMOR EPISODES ON MONTSERRAT

**B Baptie, R Luckett and J Neuberg**

The extrusive phase of the eruption of the Soufriere Hills volcano on Montserrat has been dominated by low frequency volcanic earthquakes. These earthquakes have distinctive peaked spectra and commonly occur in swarms related to the pressurization of the upper part of the magma conduit. We use data from an array of broadband seismometers to examine spatial and temporal variation in the spectral properties of these earthquakes, between January and August 1997. Although spectra are generally stable over long periods of time at a given reference point, we also find evidence changes in the spectra with time and with event magnitude, which may be attributed to changes in the source. In general, spectra are not coherent across the array. This leads to the conclusion that the wave-field is a combination of both source and propagation effects. However, during certain tremor episodes we observe harmonic spectra, with shifting spectral peaks which are coherent across the whole array. In some cases this behaviour can be modelled by repetitive triggering of low frequency events, where the harmonics are controlled by the trigger frequency or by the harmonic spectra of individual earthquakes. However, other occurrences of similar behaviour cannot be so easily explained in this way. We suggest that the shifting spectral lines may be due to the changing behaviour of interface waves, resulting from short term changes in conduit properties.

## THE BGS SEISMIC MONITORING NETWORK

**B Baptie**

The British Geological Survey seismic monitoring network occupies 145 sites across the UK. These sites include strong motion and low gain instruments. The principle 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. Data are available to the academic community through an automatic data request manager or AutoDRM. The BGS is also exploring the possibility of taking over the UK broadband network currently run by the AWE Blacknest. This would include upgrades to some of the existing stations. Data from this network would again be available through the BGS AutoDRM. Our current primary research goal is an improved understanding of crustal and upper mantle attenuation relationships in the UK. This will include the development of a local magnitude relationship, calibration with the body wave and surface wave magnitude scales and a study of the attenuation of peak ground acceleration for seismic hazard studies. In addition, we would like to develop a 3D velocity model for location of local and regional earthquakes.

## MODELLING THE VOLCANIC TREMOR ASSOCIATED WITH VULCANIAN EXPLOSIONS OF THE SOUFRIERE HILLS VOLCANO

**B Baptie**

The seismic signals accompanying vulcanian explosions of the Soufriere Hills volcano have been widely interpreted as representing the sudden release of pressurized magma through an open vent. I use a boundary element method and realistic surface topography to model the observed ground displacements. The open conduit system cannot sustain resonances of the observed durations of up to 3 hours. Therefore, I use a sequence of pressure pulses to simulate a feedback mechanism that results in observed duration of the seismic tremor. Reduction in the amplitude of the pressure pulses with time results in a decay of the tremor amplitude and simulate the damping of the tremor source. In contrast, seismic signals from explosions during the post-extrusive show a simple source wavelet after signal restitution to ground displacement that is in keeping with a contracting source mechanism.

## THE RELATIONSHIP BETWEEN VOLCANIC TREMOR AND CYCLIC GAS EXHALATIONS AT SOUFRIÈRE HILLS VOLCANO, MONTSERRAT

**B Baptie**

The renewal of andesitic dome growth at the Soufrière Hills volcano in late-1999 was accompanied by regularly spaced periods of volcanic tremor. Individual tremor events have a slow build up and rapid drop-off, and comprise long-period seismic energy. Duration of tremor episodes (3 hrs) and interval between the start of each episode (8.8 hrs) was extremely regular (total 122 tremor episodes), whilst peak amplitude of the tremor episode varied non-systematically. Gas flux was measured using a COSPEC instrument in several different modes. These data consistently suggest that peak gas flux occurs during the period of rapid drop-off of the tremor event, so that the peak in the gas flux lags the tremor peak by 30-60 mins. Gas flux ranged from <150 to >1500 $t/d^{-1}$ $SO_2$. Two- to five-fold changes in gas flux were noted within individual cycles. These new data provide substantial support for developing models of gas pressurization in the upper conduit (seismic tremor and swelling, measured by tiltmeters in 1996/97) culminating in abrupt failure of a viscous plug. Rapid extrusion of magma into the dome and rapid increase in gas flux follow and may, under certain circumstances, lead to explosive activity. The cycle repeats as rapid flow of gas out of the magma leads in turn to a renewed increase in viscosity.

## UPPER CRUSTAL P- AND S-WAVE VELOCITY STRUCTURE OF CENTRAL AND WESTERN SCOTLAND USING A JOINT HYPOCENTRE-VELOCITY INVERSION

**J D J Bott**

Central and western Scotland is one of the more seismically active regions in the United Kingdom, with over 1,000 instrumentally recorded earthquakes of $M_L \geq 1.0$ occurring between 1970 and 2000. The majority of the earthquakes are relatively shallow, occurring at depths of less than 15km. The location qualities vary across the region, but have improved overall over the past 15 years due to increased seismographic coverage. The P- and S-arrival times from a well-recorded set of earthquakes are used in a joint hypocentre-velocity inversion to improve on the general upper crustal velocity model currently used for this region. Both 1-D and 3-D velocity inversions for both P-and S-wave velocity structure are investigated. Due to a gap in the UK seismic network in central and western Scotland it is hoped that the new velocity model will improve earthquake locations. The velocity models are compared with the LISPB and BIRPS deep seismic profiles, and the structure and geology of western Scotland.

## UPPER CRUSTAL VELOCITIES AND EARTHQUAKE RELOCATIONS IN THE CENTRAL FRONT RANGE, COLORADO, FROM A JOINT HYPOCENTER-VELOCITY INVERSION

**J D J Bott, I G Wong, J Ake and S Steele Weir**

P- and S-wave arrival times from a well-recorded set of microearthquakes, (M<3.4), located in the central Front Range, Colorado, between 1983-1993, are used in a joint hypocenter-velocity inversion to improve on the earthquake locations and the velocity model. Microgeophysics (MGC) recorded these events during a 10-year period while monitoring the central Front Range for the Denver Water Department. Over 1,100 events were located during the monitoring period, many occurring in swarms and distinct spatial clusters. Original locations reveal some steeply-dipping clusters of events that suggest a possible spatial correlation with the surface traces and subsurface projections of Tertiary and Quaternary faults compiled by Widmann et al. (1998) and Kirkham and Rogers (1981). About 50 stations from the Front Range network were used in this study, which spans a region west of Denver, which stretches 140 km north to south and about 50 km east to west. Average station spacing is on the order of 10 km. There are on average 11 arrival time readings per event for the chosen data set. MGC used a layer over a half space and station delays for the location procedure. In this study we use an initial velocity model derived from seismic refraction profiles of Prodehl and Lipman (1989). A 1D joint hypocenter-velocity inversion is then used to find the minimum 1D velocity model for the region and the data set. This is then used as a starting model for a 3D joint inversion. Final relocations are compared to those of MGC and their potential association with the surface traces of any Tertiary and Quaternary faults. Implications to seismic hazard of the Denver Metropolitan area are discussed, a region which has only experienced one large naturally occurring historic earthquake, the 1882 $M_W$ 6.6 earthquake which is thought to have occurred somewhere along the northern Front Range (Spence et al., 1996).

**THE MAGNITUDE 4.2 WARWICK EARTHQUAKE OF 23 SEPTEMBER 2000**

**J D J Bott**

An earthquake with a magnitude of 4.2 ML shook the area around Warwick at 05:25 am BST, causing many residents to awake and objects to fall over. The earthquake was felt up to a maximum intensity of 5 EMS (European Macroseismic Scale) close to the epicentre and was felt over an area of 14,900 km2.

The event was recorded on most of the 146 UK seismograph stations and the arrival times of the seismic waves were used to locate the instrumental epicentre.

In the UK, over 200 earthquakes occur each year with around 30 of these being felt by the local population. On average an earthquake of this size (4.2 ML) occurs once every 2 years, with magnitude 3 events occurring three times a year. The Warwick earthquake is the largest event in the UK since the 5.1 ML Bishops Castle earthquake that occurred about 100 km WNW near the Welsh border on 2 April 1990.

Putting the Warwick earthquake into global context, over 6,000 earthquakes of this size or larger occur every year, and it was some 350,000 times smaller in terms of energy than the MS 7.9 India earthquake of 26 January 2001.

The area around Warwick has experienced few earthquakes during the instrumental period (1970-date), with only 7 located within 20 km of Warwick. Historically, similar-sized earthquakes occurred near Tewksbury in 1768; near Walsall in 1937; and near Coalville in 1940. More recently, a 3.0 ML earthquake was felt at Stratford-upon-Avon in May 1994. The Warwick earthquake was unusual in the fact that no aftershocks have been detected to date. Other similar-sized events that have occurred during the last 20 years in the UK have had at least one aftershock, if not more. The most energetic aftershock sequence followed the Lleyn Peninsula event in 1984 (5.4 ML), which had 32 recorded earthquakes within the first month, the largest of which had a magnitude of 4.3 ML.

The instrumental location of the earthquake places it just west of the west-dipping Warwick fault which, along with other parallel faults, form part of a series of Permo-Triassic and younger, steeply-dipping normal faults, with either approximate N-S or NW-SE strike. The focal mechanism indicates almost pure normal faulting on a NW-SE oriented plane, dipping either to the NE or to the SW. The style and orientation of the focal mechanism is more consistent with the NW-trending SW-dipping Whitnash fault that lies about 5 km to the east of the earthquake epicentre. Equally likely, the Warwick earthquake may have occurred on an unidentified buried fault. Seismic lines from the Worcester basin reveal many such buried faults.

**ABNORMAL HISTORIC SEA-SURFACE FLUCTUATIONS, SW ENGLAND**

**A G Dawson, R M W Musson, I D L Foster and D Brunsden**

The effects of the tsunami caused by the catastrophic 1755 Lisbon earthquake in Britain are well known; however, it is by no means the only such event. Because of its position with respect to coastlines and location of seismic sources, the south west of England is the part of the UK most likely to be affected by tsunamis. This paper presents, for the first time, an exhaustive survey of all such records, including not only those from identifiable earthquake events, but many records of tsunami or tsunami-like phenomena for which no earthquake is known. Some of these may be unknown offshore earthquakes in historical times; others may be the result of slumping on the continental slope or be meteorological in origin.

**POSTGLACIAL TECTONICS OF THE SCOTTISH GLACIO-ISOSTATIC UPLIFT CENTRE**

**C R Firth and I S Stewart**

New evidence combined with a detailed re-evaluation of postglacial fault movements, seismic activity and shoreline sequences suggests that the period of deglaciation and the early Holocene was more seismically active than the mid to Late Holocene. It is proposed that the large-scale lateral displacements formerly proposed can not be justified, rather all postglacial fault movements appear to be limited to metre-scale vertical movements along pre-existing fault lines. In addition, it is argued that the Younger Dryas ice advance may have produced localised crustal redepression but not the more widespread impact formerly proposed. Both tectonic and postglacial rebound stresses, however, may be needed to explain the contemporary seismotectonics of the Scottish Highlands.

**A SUMMARY OF EARTHQUAKES IN 2000**

**D D Galloway and B A Simpson**

**Overseas**

This year was quite exceptional in terms of the number of large worldwide earthquakes (Figure 1) and the small number of casualties resulting from them. There were 3 'great' earthquakes (magnitude over 8.0), 13 'major' earthquakes (magnitudes between 7.0 and 7.9) and 159 'strong' earthquakes (magnitudes between 6.0 and 6.9). These numbers are in general above the long-term averages for these magnitude ranges, which are 1, 18 and 120, respectively. The number of people killed by earthquakes during 2000 was 236 (Table 1) which is well below the long-term average of 8,700. This is the lowest annual death toll since 1984 when 174 people were killed and results from the larger 'major' earthquakes occurring in remote, sparsely populated areas (Figure 1).

The largest earthquake during the year, with a magnitude of 8.2 Ms, occurred on 16 November in northeast Papua New Guinea. It killed 2 people, one on Duke of York Island and one on New Ireland, and left over 5,000 homeless on Bougainville, Buka, Duke of York Island, New Britain and New Ireland. Extensive damage was reported on Duke of York Island, New Britain and New Ireland from the numerous landslides and a tsunami. The tsunami reached a height of about one metre at Rabaul and Kokopo on New Britain and 2-3 metres on New Ireland and Bougainville. Seiches up to a metre high were observed in water tanks and swimming pools at Rabaul and 2-3 metres of subsidence occurred over several hundred metres at the mouth of the Kamdaru River, New Ireland. This was the first event in a series of powerful earthquakes to occur in the area in late November. Other events in the series included a magnitude 8.0 Ms 'great' earthquake on 17 November, a magnitude 7.8 Ms 'major' earthquake on 16 November and 10 'strong' earthquakes between 16 and 23 November. These events caused additional damage in the region.

The most disastrous earthquake during the year, with a magnitude of 8.0 Ms, occurred on 4 June on Sumatra, Indonesia. It caused the deaths of at least 107 people, injured 1,052 more, destroyed or seriously damaged over 12,300 buildings and slightly damaged over 16,900 more in the Bengkulu area of Sumatra and on Enggano Island. The limits of the earthquake damage stretched from about 20 km north of Bengkulu City to a few kilometres south of the town of Manna. Many aftershocks occurred in the region after the 4 June event including a magnitude 6.7 Mw earthquake on 7 June, which caused the death of 1 person and damaged 600 buildings at Lahat.

A month prior to the Sumatra event, on 4 May, an earthquake with a magnitude of 7.6 Mw, occurred on the neighbouring Island of Sulawesi, Indonesia. At least 45 people were killed, over 260 were injured and 10,500 families were left homeless as a result of this earthquake. Extensive damage occurred in the Luwuk area, Sulawesi and on the nearby islands of Banggai and Peleng where over 80% of buildings were either destroyed or damaged. Much of the damage east of Luwuk and on Peleng was caused by a local tsunami with estimated wave heights of 6 metres.

On 14 January, an earthquake with a magnitude of 5.9 Mw, occurred in Yunnan, China. It killed 7 people, injured 1,500 more and destroyed or damaged over 31,000 homes in Yaoan County. Yunnan Province is situated in southwest China to the east of the Tibetan Plateau and is one of the areas of China most prone to natural disasters. On 21 August, a relatively small magnitude 4.9 Mb earthquake in the same general area killed 1 person, injured over 400 more, left over 169,000 homeless and caused extensive damage in the Wuding County area. A magnitude 4.9 Mb earthquake in north-east China, on 11 January, injured 30 people and destroyed or damaged some 12,000 housing units in the region.

In northern/central Iran, on 2 February, one person was killed during a magnitude 5.4 Mw earthquake in the region. Another 15 people were injured and over 400 houses were either destroyed or damaged in the Bardaskan-Kashmir area.

On 12 May, in the Atacama region of Argentina, an earthquake with a magnitude of 7.2 Mw killed one person at the Manto Verde Mine and damaged several buildings in the area. The earthquake was felt strongly throughout northern Argentina and was also felt in several towns in Chile.

In Taiwan, on 17 May, an earthquake with a magnitude of 5.4 Mw, killed 3 people, injured 13 more and caused several landslides in Tai-chung area. This earthquake was felt strongly throughout central and northern Taiwan. Three weeks later, on 10 June, a magnitude 6.4 Mw earthquake occurred in the same area, approximately 45 km from the 17 May event, and was felt throughout the whole of Taiwan. It caused the deaths of 2 people (from heart attacks) and injured 36 others in the Nan-tou area. Landslides and rockslides blocked a number of highways in central Taiwan as a result of the earthquake.

Several fatal and damaging earthquakes occurred in Turkey during the year. The first, on 6 June, with a magnitude of 6.1 Mw, killed 2 people, injured over 80 more, destroyed or damaged 4,600 homes in the Cerkes-Cubuk-Orta area and was felt in much of north-central Turkey and along the Black Sea coast. Another event, with a relatively small magnitude of 4.2 Mb, a month later on 7 July, killed one person and injured 7 more in the Gebze area and injured 27 others in the Kartal area. A further 6 people were killed, over 40 more were injured and minor damage was reported from the Afyon-Bolvadin area as a result of a magnitude 6.1 Mw earthquake on 15 December. These 3 earthquakes occurred approximately 300 km equidistant from each other in north-west Turkey.

Two earthquakes, both with magnitudes of 6.6 Mw, occurred in Iceland on 17 and 21 June. The 17 June event injured one person, destroyed 11 houses, damaged 19 others, caused rockslides which closed some roads at Vestmannaeyjar and disrupted utilities at Hella. The 21 June event destroyed 12 houses and severely damaged 24 more in the Grimsnes region.

On 1 July, a magnitude 6.2 Mw earthquake occurred near the south coast of Honshu, Japan. One person was killed, as a result of a landslide, several were injured and minor damage and power outages were reported on Kozu-shima. Many aftershocks, mostly in the magnitude range between 4 and 5, occurred in the following weeks in the same region. Another ten people were injured, over 20 more houses were damaged and more landslides and power outages occurred as a result of these aftershocks. In western Honshu, Japan, on 6 October, an earthquake with a magnitude of 6.8 Ms injured 130 people, damaged 2,230 structures, destroyed 104 houses, collapsed 7 bridges and caused 65 landslides in the Okayama-Tottori area.

In Nicaragua, on 6 July, 7 people were killed, another 42 were injured, 357 houses were destroyed, 1,130 were damaged and over 4,500 people were evacuated in the Masaya area, during a magnitude 5.1 Ms earthquake.

On 17 July, an earthquake with a magnitude of 6.4 Mw, occurred in the Hindu Kush region of Afghanistan. Two people were killed at Peshawar, Pakistan, due to the collapse of a three-storey building. The earthquake was felt in northern Pakistan, northern India, Kashmir and Afghanistan.

On Sakhalin Island, Russia, 8 people were injured, 1,390 buildings were damaged, over 19,000 were left homeless and a landslide destroyed roads and power lines during a 7.1 Ms earthquake on 4 August. Damage from this earthquake was estimated at $US 920,000.

On 9 August, a magnitude 6.5 Mw earthquake occurred in Michoacan, Mexico. Two people were killed (a three year old minor when a fence collapsed and a 62 year old from a heart attack) and four others were injured. Significant structural damage was reported from two hotels and 12 houses at Lazaro Cardenas. Hundreds of people evacuated their homes in the Michoacan region in a state of panic as they recalled the 1985 Mexico earthquake which left some 10,000 dead and caused widespread destruction in the region.

Near the coast of Ecuador, on 20 September, one person was killed, several others were slightly injured and damage occurred in the Manabi Province during a magnitude 5.5 Mw earthquake in the region.

On 10 November, in northern Algeria, one person was killed in Bouga, another was killed in Chemini and 12 others were injured and 7 houses destroyed in Beni Ourtilane during a magnitude 5.8 Mb earthquake.

Two earthquakes within a minute of each other, both with magnitudes of 6.3 MW, occurred in Azerbaijan on 25 November. The epicentres were in the Caspian Sea, 25 km east of Baku, the capital of Azerbaijan. At least 31 people were killed; 5 by falling debris, 23 from heart attacks and 3 were killed the following day by an explosion caused by natural gas leaking from a pipe damaged in the earthquake. Over 430 others were injured and some damage was reported from the Baku area. The earthquake affected the north-east coastline of Azerbaijan and most of the damage occurred between the Absheron Peninsula and the Russian border. It was felt as far away as Tbilisi, Georgia, 600 km north-west of the epicentre.

In Turkmenistan, on 6 December, an earthquake with a magnitude of 7.5 Ms, killed 11 people, injured dozens more and caused much damage in the Nebitdag-Turkmenbashi area. The earthquake was reported felt throughout the region including much of southern Russia, and as far away as Moscow, some 2,000 km to the north-west.

The UK summary of earthquakes is covered in the summary for the 2000 bulletin of British earthquakes above.

**UNIFIED SEISMIC HAZARD MODELLING THROUGHOUT THE MEDITERRANEAN REGION**

**M J Jiménez, D Giardini, G Grünthal, M Erdik, M Garcia-Fernández, J Lapajne, K Makropoulos, R M W Musson, C Papaioannou, S Riad, S Sellami, A Shapira, D Slejko and T. van Eck**

A project entitled SESAME was established as the successor to the GSHAP project in Europe, with the aim of improving the seismic source model for the Mediterranean region according to homogeneous procedures. This paper presents the current status of the model and preliminary results.

**RECORDING AND DELIVERING SEISMIC AND GEOMAGNETIC DATA**

**D Kerridge and S Flower**

Following earthquakes and magnetic storms there is a high level of demand for prompt access to information from a range of BGS customers. BGS produces the data needed to respond to customers by operating the UK's seismic network and magnetic observatories, which are equipped with sensors continuously monitoring seismic and geomagnetic activity. Because the systems are recording geophysical time-series data, a high level of instrument reliability and continuity of recording is vital - if a piece of equipment is out of action when an interesting event occurs the opportunity to record that event is lost forever. Reliable collection of data from the sensors, and efficient methods for transmission of the data to the BGS offices in Edinburgh for analysis and subsequent dissemination of data products, are essential in providing the level of service expected by customers. This article describes the recording and communication systems that have been developed to ensure that high standards of service are achieved.

**SEISMIC SIGNALS ASSOCIATED WITH DOME ROCKFALLS ON SOUFRIERE HILLS VOLCANO, MONTSERRAT**

**R Luckett, B Baptie, and J Neuberg**

One of the most common types of seismic event recorded during the ruption of Soufriere Hills volcano is known as a rockfall signal because signals recorded when rockfalls are observed on the dome are f this type. There is more to these signals than purely the seismicity generated by falling debris, however. Evidence is presented hat a second seismic source also contributes to these events and the recent deployment of a pressure sensor near the volcano has shown that this seismicity is associated with de-gassing at the surface of the dome. It is likely that this de-gassing is what causes the rockfall in the first place.

**EVALUATION OF SEISMIC HAZARD SOURCE MODELS**

**R M W Musson**

Whether or not the use of zoneless seismic hazard models is to be preferred over traditional approaches, the debate over their use has at least had the welcome effect of stimulating more discussion about different methods and approaches to probabilistic seismic hazard modelling. An argument often used in support of zoneless approaches is the absence of criteria for defining seismic source zones in practice. This is illustrated by case histories where wildly different seismic source zones have been proposed by different workers for the same area, often bearing little resemblance to reality. Such a line of argument certainly points to the fact that some existing studies are less than satisfactory, but the fact that zone models can be produced in an arbitrary or careless fashion is more a criticism of some practitioners rather than a real criticism of the method itself. What is needed is not an abolition of source zone models from seismic hazard assessment, but better guidelines for defining them and evaluating them.

The absence of evaluation in previous studies is rather noticeable. While it may be common to find discussions of the reasoning that led to the construction of a certain set of source zones, one seldom sees any sort of post-design testing to demonstrate that the construction is good. And whereas in the past the seismic hazard analysts' work has often been taken on trust by clients, it is quite possible that in future it will be more common to find some sort of verification of results being requested. In which case some procedures need to be in place beyond subjective peer review. Four approaches are discussed here:

The argument from sensitivity: Some design decisions in source modelling can be justified on the simple grounds that from the point of view of site hazard, alternative interpretations make no practical difference. At distance from a design site, one can make quite crude modelling decisions for simplicity's sake, and show that finer discrimination of source geometry actually makes no difference.

Nearest neighbour analysis: Seismic source zones are supposed to be homogeneous with respect to earthquake distribution within each zone. Is this ever tested? Nearest neighbour analysis provides a tool to do exactly that. A zone model that fails the test is not necessarily a bad one, but there have to be good arguments ready to explain the inconsistency.

Testing by simulation: A seismic source model can be used to generate synthetic earthquake catalogues that should resemble the real earthquake catalogue at least to a general degree. Badly made source models often give quite unreasonable synthetic catalogues. This is a simple and useful test.

Comparison with experience: In areas where there is a long history of intensity observations it is possible to compare computed seismic hazard with actual experience. Any systematic differences suggest that something may be wrong, which needs to be investigated further.

**ON THE TRANSITION FROM PROBABILISTIC SEISMIC HAZARD TO PROBABILISTIC SEISMIC RISK**

**R M W Musson**

Any survey of the literature on seismic hazard studies will reveal that the majority of hazard maps and curves produced are expressed in terms of peak ground acceleration, or occasionally spectral acceleration. This is because the perceived users of hazard studies are engineers, who require such physical values for design purposes. However, earthquakes are also of concern to planners, insurers and politicians. Such people are not concerned with design parameters, and need information in other forms, principally in terms of damage and loss expectations. In other words, seismic hazard is less important, and seismic risk is more important. For this, intensity provides a good dimension, as it relates specifically to damage in a way that physical parameters like peak ground acceleration do not. The passage from hazard to risk is still problematic using older intensity scales (RF, MCS, MMI), but since the MSK and the EMS-98 intensity scales directly express the probabilistic nature of damage distributions for any intensity degree, the task is greatly simplified. With EMS-98 intensities one has the best tool yet for estimating seismic risk as the necessary vulnerability functions are integrated into the scale in such a way as to take into account most possible building situations, from poor quality masonry to modern engineered constructions with earthquake-resistant design. Because damage in EMS-98 is represented as a series of probability functions, it is relatively easy to adapt seismic hazard calculation processes to fully probabilistic seismic risk. Attention needs to be directed now to tackling some of the problems that are thrown into relief in practising intensity-based seismic risk studies, such as the categorisation of assemblages of structures at risk, regional analyses of the attenuation of EMS-98 intensities, and analysis of local intensity variations due to soil conditions. A potential problem is the assessment of loss to large buildings, since these can not be so easily generalised. More research is needed to see to what extent it is possible to give generalised seismic risk evaluations for the entire built environment that are sufficiently robust to be useful.

## THE HISTORICAL SEISMICITY OF PLACES WITH NO EARTHQUAKES

**R M W Musson**

Studies of historical earthquakes are more often done today for a practical purpose such as seismic hazard analysis than merely for antiquarian or general scientific interest, although this was the motivation of the great catalogues of the 19th century. Since seismic hazard is most of concern in areas where earthquakes are an obvious threat, it follows that such studies tend to concentrate on areas of high seismicity. However, sometimes it is necessary to demonstrate quantitatively that seismic hazard is low in areas that are apparently free from earthquake activity. The question can be put: is the absence of earthquakes in an area due to there really not being any, or is it due to the fact that data sources are deficient, or no-one has even looked for historical earthquakes there? In the extreme case, it may be that an area is truly aseismic and it becomes the task of the seismologist-historian to demonstrate this by examining sources that might contain earthquakes and showing that they do not do so. In such a case the task emphasises the methods of the historian in examination of sources, and consideration of the cultural conditions that may have affected the transmission of earthquake data. In this paper the problem of proving a historical negative is considered with respect to two case histories in areas of extremely low seismicity: Ireland and the Faroe Islands.

## THE SEISMICITY OF CORNWALL AND DEVON

**R M W Musson**

In the 36 years since ATJ Dollar presented his paper on the seismicity of the Cornubian Peninsula in relation to structure, a great deal has changed in the understanding of British seismicity, both in terms of knowledge of its distribution and parameters, and in terms of its geological and tectonic setting. This is as true for Cornwall and Devon as for other parts of the UK. Since the late 1970s a large amount of effort has been directed into research on historical earthquakes in the UK, undertaken with a critical approach to the appraisal of historical sources, something previously lacking in studies of historical earthquakes. During the same period, modern instrumental monitoring has been improved. The need for seismic monitoring of the geothermal energy project at Rosemanowes led to a dense local network capable of recording and locating even very small natural events. In terms of average UK seismicity rates Cornwall and Devon are neither as seismic as the most active areas (such as NW Wales) nor as quiet as the most inactive areas (such as NE England). While earthquakes in the area occasionally cause public alarm, they seldom exceed 4 ML in magnitude and have caused very little damage in the last 250 years. The distribution of seismicity is irregular; most activity is concentrated in three zones: the Penzance-Helston area; an area running from off the north coast of Cornwall, through eastern Cornwall to south Devon, and the Barnstaple-Ilfracombe area. Relating this distribution to geological structure is a contentious issue. Some major structures such as the Sticklepath Fault, (which has a reputation as being “active” seismically) do not show up at all. It is likely that the distribution is influenced by the interaction of local structures and reactivation along lines of old E-W thrust faults of Variscan age.

## INTENSITY-BASED SEISMIC RISK ASSESSMENT

**R M W Musson**

Recent experience suggests that the bulk of modern studies of seismic hazard have sought to express ground motion in terms of physical parameters such as peak ground acceleration, spectral acceleration, and so on. For the purposes of providing design parameters for engineering projects this is obviously a sensible approach. However, when dealing with estimations of seismic risk, that is, the estimation of future probabilities of damage to existing structures, it is not so clear that this is the best procedure. The correlation of physical ground motion parameters with actual levels of damage has proved a difficult subject of study. No single ground motion parameter (such as peak ground acceleration) provides an ideal analogue of damage, although there are some hopeful avenues of approach using more complex combinations of spectral parameters.

However, the problems can be bypassed by using earthquake intensity in place of physical ground motion parameters. Intensity relates specifically to damage in a way that parameters like peak ground acceleration do not. The passage from hazard to risk is still problematic using older intensity scales (RF, MCS, MMI), but since the MSK and the EMS-98 (European Macroseismic Scale) intensity scales directly express the probabilistic nature of damage distributions for any intensity degree, the task is greatly simplified. With EMS-98 intensities one has the best tool yet for estimating seismic risk as the necessary vulnerability functions are integrated into the scale in such a way as to take into account most possible building situations, from poor quality masonry to modern engineered constructions with earthquake-resistant design.

It follows that an equation that expresses the attenuation of EMS intensities is a description of the extent to which damage patterns to different building types vary as a function of magnitude, distance, and in some cases, azimuth. Such an equation is based directly on past observations of damage, and so it is only natural to expect it to do a reasonable job of predicting future levels of damage. The difficult question of damage functions for ground motion parameters is thus side-stepped completely.

Risk curves can be prepared that show the probability of different grades of damage being suffered by buildings of different types. Given a system for relating damage grade to the actual cost of repair as a function of the value of the building, it is possible to calculate seismic risk as curves showing the probability of loss in financial terms – useful for planners and insurers.

Attention needs to be directed now to tackling some of the problems that are thrown into relief in practising intensity-based seismic risk studies, such as the categorisation of assemblages of structures at risk, and regional analyses of the attenuation of EMS-98 intensities.

**MODELS OF TREMOR AND LOW-FREQUENCY EARTHQUAKE SWARMS ON MONTSERRAT**

**J Neuberg, R Luckett, B Baptie and K Olsen**

Recent observations from Soufriere Hills volcano in Montserrat reveal a wide variety of low-frequency seismic signals. We discuss similarities and differences between hybrid earthquakes and long-period events, and their role in explosions and rockfall events. These events usually occur in swarms and occasionally merge into tremor, an observation that can shed further light on the generation and composition of harmonic tremor. We use a 2D finite difference method to model major features of low-frequency seismic signatures and compare them with the observations. A depth dependent velocity model for a fluid-filled conduit is introduced which accounts for the varying gas-content in the magma, and the impact on the seismic signals is discussed. We carefully analyze episodes of tremor that show shifting spectral lines and model those in terms of changes in the gas content of the magma as well as in terms of a time-dependent triggering mechanism of low frequency resonances. In this way we explain the simultaneous occurrence of low-frequency events and tremor with a spectral content comprising integer harmonics.

**GLACIO-SEISMOTECTONICS: ICE SHEETS, CRUSTAL DEFORMATION AND SEISMICITY**

**I S Stewart, J Sauber and J Rose**

The last decade has witnessed a significant growth in our understanding of the past and continuing effects of ice sheets and glaciers on contemporary crustal deformation and seismicity. This growth has been driven largely by the emergence of postglacial rebound models (PGM) constrained by new field observations that incorporate increasingly realistic rheological, mechanical, and glacial parameters. In this paper, we highlight some of these recent field-based investigations and new PGMs, and examine their implications for understanding crustal deformation and seismicity during glaciation and following deglaciation. The emerging glacial rebound models outlined in the paper support the view that both tectonic stresses and glacial rebound stresses are needed to explain the distribution and style of contemporary earthquake activity in former glaciated shields of eastern Canada and Fennoscandia. However, many of these models neglect important parameters, such as topography, lateral variations in lithospheric strength and tectonic strain built up during glaciation. In glaciated mountainous terrains, glacial erosion may directly modulate tectonic deformation by resetting the orogenic topography and thereby providing an additional compensatory uplift mechanism. Such effects are likely to be important both in tectonically active orogens and in the mountainous regions of glaciated shields. In general, the short-term response to ice fluctuations is similar to the Earth's response to fluctuations in water reservoirs with the subsequent increase or decrease in seismicity which depends on the pre-existing stress state. When the ice fluctuations occur on the spatial scale, and magnitude, of the Late Pleistocene glaciation and deglaciation, however, the viscoelastic response of the Earth (especially the mantle) causes significant changes in crustal deformation and earthquake activity that is spatially extensive and temporally complex. The regions of greatest ice thickness and the regions marginal to the Late Pleistocene ice sheets indicate the most dramatic evidence of earthquake faulting. The mantle response to these large ice mass fluctuations and the change in mass between the oceans and land caused, and continues to cause, measureable crustal deformation at hundreds of kilometres from the ice margins.

For both tectonically active and cratonic regions, palaeoseismic investigations of Late Pleistocene and Holocene faults are an important tool in evaluating earthquake hazard. The predicted response of the Earth over this time, however, is very dependent on the model assumed. For most regions, far more carefully designed field observations are needed to constrain the existing rheological and ice models.

## 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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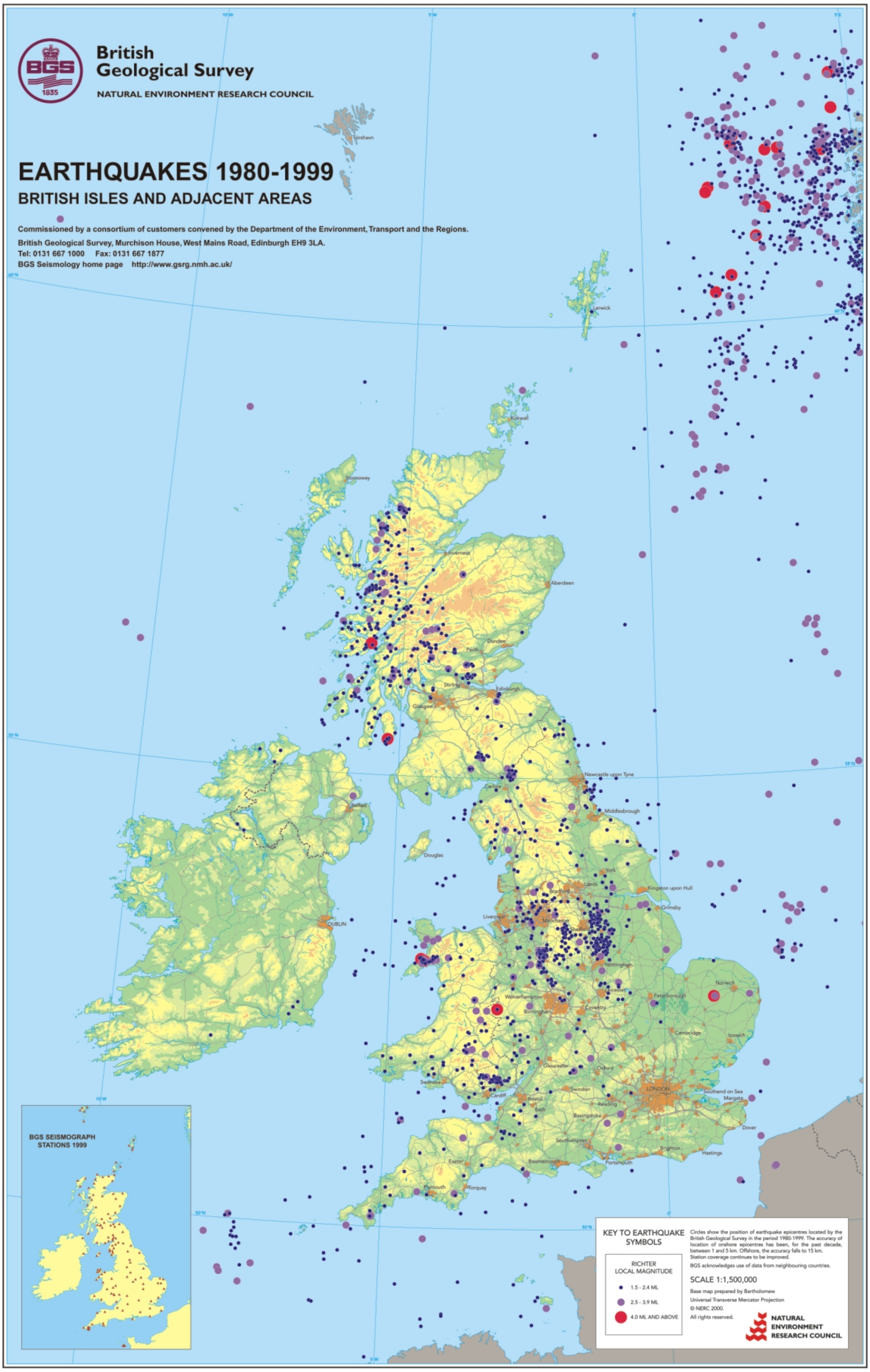


A wall map of earthquakes in the British Isles and adjacent areas, 1980 - 1999.