UK EARTHQUAKE MONITORING 1999/2000

BGS Seismic Monitoring and Information Service

Eleventh Annual Report

British Geological Survey
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BRITISH GEOLOGICAL SURVEY

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Global Seismology and Geomagnetism Group

UK Earthquake Monitoring 1999/2000

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Eleventh Annual Report

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

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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.

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

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UK EARTHQUAKE MONITORING 1999/2000

1. Executive Summary

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.

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 subsidence, and other tremors (eg sonic booms and explosions) are often mistaken for earthquakes.

This Year 11 report to the Customer Group follows the format of the first ten annual reports in reiterating the programme objectives and highlighting some of the significant seismic events in the reporting period, April 1999 to March 2000. The catalogue of earthquakes for the whole of 1999 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, low-gain and strong motion instruments have been added to it. Low-gain instruments employ standard seismometers recording ground velocity but with the electronic amplifier gain reduced by a factor of 25. Strong motion instruments record ground acceleration for the larger felt earthquakes, remaining on-scale up to 0.1g. One new strong motion system has been installed during the year, near Dounreay, northern Scotland, bringing the total to eighteen. 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.

The six temporary broadband stations installed throughout the country in collaboration with Leeds and Bristol universities are continuing to collect data on UK and world earthquakes. They record onto computer disks containing up to three months of data, which are then changed by an operator and analysed at the University of Leeds. The BGS broadband station in Edinburgh 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.

BGS has recently taken over the MOD broadband network which was operated by AWE Ltd (Atomic Weapons Establishment) at Blacknest. The intention in the first instance, is to evaluate the network and its potential for integration into the BGS system before embarking on an upgrade programme.

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 and northern Scotland. 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 2000. 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 11-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 to provide a 3-day ring buffer at seven nodes and up to 10-days at the other seventeen.

- 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 have been made available on-line for down-loading.

- 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 is now in the DTI library and through BGS.

- 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 Met 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 30-year catalogue and digital archive of earthquakes, during the past year, is summarised:

3.2.1 University collaboration

Bristol University; Mapping seismic discontinuities

A study at Bristol University, under the leadership of George Helffrich, has continued to look at seismic discontinuity mapping using teleseismic data (earthquakes outside the UK).

The earth's major seismic discontinuities in the mantle are at 410 and 660 km depth and are believed to be caused by phase changes in mantle minerals. Seismic waves generated by interaction with discontinuities are weak and usually buried in the noise but the high density of stations in the UK network provides the means to enhance the signal and suppress noise. The Bristol team is using UK and North American data to study the effect that subduction zones have on these seismic discontinuities and to infer their temperature and chemical state at depth. To date, results show that the discontinuities are deflected by the cooler temperatures in subducted slabs to a much greater degree than is observed in global studies using long period seismic waves. Temperatures are about 600°C at 350 km depth in the slab, and the thermal halo around the slab is broader than expected from thermal modelling. The work has provided the basis for further research through a NERC studentship.

A joint study involving Bristol University and the BGS is investigating scattering and heterogeneity in the crust and the deeper mantle using echoes from distant earthquakes.

One thinks of the earth's crust and mantle as a homogeneous ball of rock, but it isn't - continents and oceans otherwise wouldn't exist. The smaller scales of this heterogeneity reveal how the crust was formed: through faulting, magmatic growth and tectonic accretion. This work uses UK and foreign seismic networks to locate places in the crust that scatter seismic waves forming faint echoes following an earthquake. For crustal scatterers, nuclear tests in Kazakhstan will be used to interrogate the region around the test site and relate them to regional geological features and incorporate them into yield estimates from nuclear tests. Scattering also happens in the mantle. Prospecting for mantle scatterers will focus on three regions: one at the core-mantle boundary under northern Asia using northwestern Pacific earthquakes, another under the mid-Pacific at the core-mantle boundary using nuclear explosions at Muraroa, and lastly under the central Atlantic ocean near the Cape Verdes hotspot using mid-Atlantic fracture zone earthquakes. The scatterers will be related to the documented core-mantle boundary structures under Asia, the Pacific, and the location of the Cape Verdes hotspot. The work has provided the basis for further research through a NERC studentship.

Post-doctoral research at Bristol University, under the leadership of George Helffrich, is using the UK short-period network data to study changes in the time it takes seismic waves to cross the inner core.

In addition to providing the chronology for plate motion histories, geomagnetism gives life on the Earth a means of navigation and protection from the harmful effects of charged solar particle fluxes. To understand geomagnetism, we need to know the dynamical behaviour of the earth's core. Comprehension of core dynamics is at the level where two computer simulations of the Earth's geodynamo, in a three-dimensional spherical geometry, yield Earthlike magnetic fields. The simulations principally differ in the role played by viscous coupling between the inner and outer cores, and can be distinguished by their prescribed rates of inner core rotation. The inner core rotation rate also is related to the temperature and light element release profile along the inner core boundary and the toroidal magnetic field strength there. We are using the BGS's unique dataset, spanning 25 years, to definitively address this crucial issue concerning core dynamics, and to further elucidate the structure of the inner core.

Brunel University; Glaciotec project

The Glaciotec project, led by Iain Stewart, is a multi-disciplinary investigation of recent crustal movements, postglacial faulting and seismicity associated with the glacio-isostatic rebound. The research has focused principally on the Scottish glacio-isostatic uplift centre and has largely involved a critical reappraisal of previously reported field evidence for palaeoseismicity and neotectonism in the western Scottish Highlands. The **Glaciotec** project, however, is part of an INQUA-supported research initiative investigating 'Ice Sheets, Crustal deformation and Seismicity'. A special issue of *Quaternary Science Reviews* on 'Glacio-seismotectonics: Ice Sheet, Crustal Deformation and Seismicity' is due for publication in September 2000, and is co-edited by Iain Stewart, Jeanne Sauber (NASA), and Jim Rose (Royal Holloway). The special issue integrates general review articles on postglacial rebound models and crustal deformation contains case studies, mainly from Fennoscandia, North America and the British Isles. The general consensus of the volume is that both tectonic stresses and glacial rebound stresses are needed to explain the distribution and style of contemporary earthquake activity in many former glaciated shields.

Glaciotec research in Scotland has undertaken a detailed re-evaluation of postglacial fault movements, seismic activity and shoreline sequences. The findins suggest that there is evidence for a brief pulse of enhanced seismotectonic activity in northern areas of the UK during deglaciation of the main British (Devensian) and later Younger Dryas (Loch Lomond) ice masses. This activity is manifest as Lateglacial soft-sediment deformation phenomena and postglacial surface fault movements in western Scotland. However, previously reported evidence for large-scale (tens to hundreds of metres) horizontal displacements on postglacial faults in Scotland is considered spurious, and the faults are instead considered likely to exhibit only metre-scale vertical movements. The timing of such movements are found to be only loosely constrained, and the suggestion of a rotation of the stress field between early postglacial and modern times is rejected. The Scottish postglacial faults may well mark the distributed reactivation of favourably oriented basement structures at the receding margins of a decaying ice sheet. Evidence for fault reactivations accompanying earlier stages of the deglaciation of the main British ice sheet ought to be found in southern and northern Ireland.

No postglacial faults are reported for England and Wales but soft-sediment deformation structures in south-west England and possible late Pleistocene faults in Ireland may be evidence of earlier glacio-seismotectonics. Future Glaciotec research will extend the studies to southern Britain, while research in Scotland will pursue the detailed investigation of possible postglacial faults using airborne TM and CASI imagery (collected as part of a NERC flight-time award with Dr Bill Murphy, Portsmouth University).

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.

James Tomlinson (Leicester University) has begun his PhD (funded by the BGS) on a teleseismic receiver function and gravity study of UK crustal structure. He has initially examined data from a Canadian station, beneath which the crustal structure is well constrained from controlled source deep seismic profiles, in order to master the receiver function method. He is now applying a GA method to invert the resulting receiver functions into velocity-depth models. A 6 month visit to Murchison House in Edinburgh will be used to acquire the necessary data for the next stage of producing 1-D models beneath suitable UK stations.

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 geology architecture. Residual pressure differences at depth derived from the density model will be examined in relation to present UK seismic activity.

Leeds University

Leeds and Bristol Universities' broadband stations, which are co-located with BGS short period instruments, have continued to operate (Fig. 6). Their principal focus is the investigation of discontinuities and scattering in the Earth's mantle but data will be available to BGS following significant UK earthquakes, where BGS will utilise the datastream.

Cambridge University- Atlantic Margins Project

The Atlantic Margins Project (AMP) is investigating the deep structure of the Faroe-Shetland, Rockall-Hatton and Porcupine trough regions using deep seismic reflection and refraction profiling, integrated with potential field studies. The research provides constraints on 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 June 1999 the project collected wide-angle Ocean Bottom Seismograph (OBS) and deep reflection seismic data along two profiles over the Faroe-Shetland Trough and Shetland Platform, using a large airgun array. Ray-tracing the OBS data provides well constrained models of the crustal structure and depth to the Moho; while the reflection data provides a detailed image of the crustal structure. While these data were being acquired the airgun shots were recorded by the BGS land stations located on the Shetland Islands. The data show clear arrivals to offsets of greater than 200 km; corresponding to refracted energy from the upper mantle. Recording the airgun shots to these very long offsets provides vital information about the velocity structure of the upper mantle and Moho discontinuity, thereby helping to determine the nature and extent of any underplated material in this region. Following the success of the land recordings in 1999, it is hoped to repeat this procedure during acquisition west of Scotland in summer 2000.

The AMP research team comprises Richard Hobbs, Rose Edwards and Frauke Klingelhoefer at University of Cambridge and Richard England at University of Leicester.

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, Faroe Islands, has resulted in the deployment of a 5-station network linked to the UK system. It has improved, considerably, the monitoring of seismic events offshore northern and western Scotland, with the magnitude 3.0 ML earthquake of 29 September demonstrating the capability.

Major international projects that have drawn upon the UK database include the Global Seismic Hazard Assessment Programme (GSHAP), an IDNDR project from which hazard maps and reports have been published recently. This major international project was one of the key activities of the International Decade for Natural Disaster Reduction (IDNDR). BGS was involved at all stages of the project, and as well as being involved in the data preparation and computation of hazard for the British Isles, was also the key responsible for the North Balkan area.

An EC-funded project (Basic European Earthquake Catalogue and a Database (BEECD)) set up to prepare a basic parametric earthquake catalogue of Europe and a database of primary data, with special reference to long-term seismicity, has been completed this year.

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

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. A series of hazard and risk maps for Scotland were prepared for an invited paper at a special symposium on seismic hazard at the IASPEI conference in Birmingham in July 1999 (see Annex G for abstracts).

BGS now uses its own in-house software for seismic hazard calculations, and this has been upgraded during the year to include features for full handling of fault sources, calculation of rupture hazard, production of hazard profiles (e.g. for pipelines) and identification of design earthquakes. The software can also model attenuation as a variable, as a function of azimuth. It was used within the Global Seismic Hazard Assessment Programme (GSHAP) project, which was completed this year, for the computation of hazard maps for the North Balkan region, where one of the principal seismic sources (the Vrancea seismic zone) is highly directional in its effects.

Reinsurance

In the report last year, a description was given of a computer program that can quickly assess the earthquake risks to a reinsurance portfolio, developed by the British Geological Survey in conjunction with Hiscox Syndicates Ltd. This program combines an application of the BGS earthquake database with Monte Carlo simulation methodology to give direct estimates of seismic risk (as opposed to seismic hazard, i.e. concerned with actual loss and not merely ground motion). A series of papers and presentations have been given to demonstrate the methodology to a wider audience. The program itself has been enhanced from its first released version, to make the program 32-bit in operation and improve performance generally. A second version of the program with important new features, including support for deductibles and reinstatements has been under development and is almost complete. These products have been designed to utilise the BGS national database of earthquakes and to attract cofunding from the insurance sector into the UK seismic monitoring and information service.

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, thirteen three-component strong motion records have been recorded for earthquakes with magnitudes between 1.1 and 4.0 ML at distances of between 3 and 135 km. Five of these records were written in the past reporting year. The values of acceleration measured from these instruments are less than those expected from the attenuation laws currently used for the UK. However, most of these relations are not appropriate for smaller magnitude earthquakes. Attenuation of smaller events tends to be higher than for larger events because of the high frequency content which attenuates faster. Of necessity, these laws have been imported from more highly seismic regions using earthquakes with larger magnitudes and the build-up of UK records will eventually permit more appropriate relationships to be established for use by engineers in this country.

Strong motion and weak motion data has been supplied to consultants for the nuclear customers' Industry Management Committee (IMC) which has funded modelling studies to predict ground motion characteristics from larger magnitude earthquakes in the UK.

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, since broadband recordings contain much more information than their short period counterparts. However, as well as containing information on the nature of the seismic source, teleseismic data recorded on broadband seismometers may also be used to improve our understanding of crustal structure in the locality of the instrument. A number of methods can be used to image heterogeneity in the crust and upper mantle. Improved understanding of crustal structure leads to greater accuracy in the determination of UK earthquake epicentres, focal mechanisms and the crucial (for hazard assessment) depths of occurrence.

Teleseismic P-waves from distances greater than 40° produce conversions at boundaries in the crust and multiple reverberations in shallow layering. The first 20-30 seconds of the waveform therefore contains information about the local structure. Broadband receiver functions can be used to determine the shear wave velocity structure in the upper 35km or so, beneath individual stations. Surface wave phase velocities are sensitive to the S-wave velocity structure, so can be used to constrain the crustal velocity model. Local tomography utilizes criss-crossing raypaths from nearby earthquakes to seismic stations in joint inversions to determine both source locations and crustal structure. Teleseismic waves recorded on an array can be used to invert for three dimensional crust and upper mantle heterogeneity beneath the array.

The BGS currently operates a single permanent broadband station at Edinburgh. Broadband data are also readily available from the IRIS station at Eskdalemuir. In addition, data from a temporary array of broadband sensors installed by Leeds and Bristol Universities is also available to BGS for study of local earthquakes and crustal structure, for the limited period that the array is in place. Finally, the BGS has recently assumed sole responsibility for the operation of a UK broadband array previously operated by AWE Ltd. After upgrading, continuous broadband data should be available from up to six stations across the southern half of the UK.

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

Over 2000 enquiries have been answered during the year, with intense interest following felt UK events and the devastating world earthquakes in Turkey, Greece and Taiwan. This level of interest has exceeded that in an average year when about 1000 enquiries are addressed.

Data exchange and world reporting

BGS data is exchanged regularly with European and world agencies to help locations 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, from the 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 provisional international data centre in Washington.

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 Plate 1, 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. Plate 2 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) and in 1984 (North Wales). To determine the seismogenic thickness of the earth's crust across the UK, earthquakes with A, B or C quality locations are plotted as a function of depth. The geographic distribution (see back cover) shows that the depths at which earthquakes occur vary across the UK. The majority of earthquakes in Scotland are relatively shallow (≤ 15 km), whereas in Wales, earthquakes occur at greater depths (10-25 km). This demonstrates a difference in the seismogenic thickness of these two regions. Earthquakes in Cornwall are fairly shallow 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.

Focal mechanisms

Earthquake focal mechanisms are a basic tool used in the investigation of both local and regional tectonics, providing information on the nature of the brittle crust. In the past, mechanisms could only be obtained for the largest events but as a result of the expansion of the UK network over the years, an increasing number are being determined for smaller ones as these are well-detected on several stations. Focal mechanisms are also being obtained for very small magnitude events in areas with an optimum azimuthal coverage by dense local networks, for example North Wales, Cumbria and Cornwall. Three focal mechanisms were obtained during 1999 for the Arran, Hereford and Sennybridge earthquakes (Walker, 2000). The latter two showed predominantly normal faulting with components of strike slip and the Arran earthquake was predominantly strike-slip. As more focal mechanisms are constrained, a better understanding of the stresses which cause earthquakes in the UK can be determined.

Public Understanding of Science

A number of presentations have been given to school and university students and other interested parties. Over 600 media interviews have been conducted, including 147 for TV broadcasts and 182 for radio, (Plate 3) following significant earthquakes. The BGS was featured in an 'ology' hour programme broadcast on BBC Knowledge and a contribution has been made to the BBC's 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 132,000 visits in the year. It is listed in the New Scientist web site as one of its best links for earthquake information. BGS, in collaboration with UKAEA, produced a booklet explaining some of the fundamental principles of seismology. This was distributed to the Customer Group and is being used in school educational packs and for general enquiries.

4. Development of the monitoring network

4.1 Station distribution

The network developed to March 2000, with rapid-access upgrades, is shown in Figure 1 with its detection capability in Figure 3. The scheduled programme for 1999/2000 had as its aims:

(i) Further installation of the QNX operating system.

(ii) Extend coverage across to the Faroe Islands in collaboration with the Faroese Museum of Natural History and the oil industry GEM (Geotechnical Environment and Metocean) group.

(iii) Progress evaluation of year 2000 provisions.

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

(v) Introduction of two new strong motion systems at sub-network digital acquisition centres, priorities being northern Scotland and Swansea.

(vi) Pursue opportunities for capturing more strong motion data in collaboration with the nuclear industry.

(vii) Collaborate with universities to secure further broad band data.

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

Two QNX systems (i) have been installed in the Faroe Islands and the Orkney network. A five station network was completed in the Faroe Islands (ii) in November 1999 and is contributing essential data for locating earthquakes in the north west Atlantic ocean. The network continued to function throughout the critical year 2000 period (iii) with all data being successfully transferred and analysed. The installation of additional four gigabyte disks (iv) has been fulfilled; at Hartland, north Devon and Hereford. The strong motion network (v) has been enhanced with the installation of one strong motion station, at Reay, northern Scotland, which is recorded onto the rapid-access system. This brings the total number to eighteen. During the year, a further five strong motion records have been obtained from the Hereford, Jersey, Johnstonebridge, Sennybridge, and Dumfries earthquakes (vi). Collaboration with the universities of Bristol and Leeds has been maintained (vii). BGS has officially taken over the MOD broadband stations, previously operated by AWE Ltd and is in the process of evaluating the network with regard to upgrading the equipment. Contact with archives outside BGS has been maintained (viii).

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 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 five earthquakes this year; the Hereford, Jersey, Johnstonebridge, Sennybridge and Dumfries 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. 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.

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 HSE, has continued with funding assured until March 2001.

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 network was not year 2000 (Y2K) compliant and considerable effort was put into solving the problems, with the successful installation of Y2K patches on the existing SEISLOG recording systems, all of which worked over the critical Y2K period.

The new data acquisition equipment, using the QNX operating system, is now installed at four locations; Lowlands (around Edinburgh), Eskdalemuir (Scottish Borders), Faroe Islands and the Orkney network. QNX gives a number of advantages over the SEISLOG systems; increased processing power, larger memory capacity (from 4 Mb to upwards of 32 Mb), improved communication links using Ethernet cards and ISDN links (digital telephone lines), together with greater portability.

Thirteen of the networks in the UK have four gigabyte disk storage, (three installed in the past year), allowing up to 10 days of continuous data to be recorded in a ring buffer, together with extra storage for event files which are needed during swarms. These large capacity disks help prevent potential losses as the old analogue Geostore recorders are decommissioned and reliance swings to the event-triggered systems which can miss spurious events, small earthquakes and sonic booms. Seven networks have 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 city centres now have air pollution monitoring equipment but the 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. The existing infrastructure of the UK seismograph monitoring network, with its remote stations giving continuous on-line data from the Faroe Islands to Jersey, can potentially provide a cost-effective environmental monitoring network. Users can inspect the data in real-time or transfer it at intervals via modem or the Internet. In principle, any environmental sensor can be interfaced and sampled at, say, once per minute.

Currently, there are four environmental stations in operation in southern Scotland; Loanhead, on the outskirts of Edinburgh, Stoney Path and Dunslair, the latter, is operated in collaboration with the Institute of Terrestrial Ecology (ITE), and at the BGS Eskdalemuir Observatory. The concept was developed with limited sensors at the first three sites and a full demonstration system was installed at Eskdalemuir during 1999. Its capability in pollution and environmental monitoring comprises UVB, ozone, sulphur dioxide, nitrogen oxides, wind velocity, air temperature, soil temperature, rain fall, humidity, surface wetness, solar radiation and sunshine. The data at the Observatory site are recorded using a Campbell Scientific logger and a BGS designed logger, which are interfaced to a PC computer. The Eskdalemuir site has the advantage of being a Meteorological Office site and direct comparisons between the Met. 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 a limited range of sensors, which are transmitted directly to the Edinburgh recording site. Stoney Path, the original test site installed by BGS, has sensors which monitor UVB, air temperature, ground temperature, humidity and nuclear radiation. The data from these out-stations can be accessed via a simple to operate Windows based programme, which enables daily plots of the recorded data to be viewed and printed.

Selected 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. An EC funded collaborative project with the BGS Analytical and Regional Geochemistry Group (contact Dr R A Nicholson) has been under way since September 1998. Its purpose is to explore earthquake prediction potential through the measurement of radon flux and a radon monitoring site has been installed near Blackford in Perthshire, Scotland with the data transmitted for continuous recording in Edinburgh. It demonstrates another possible environmental parameter for incorporation into a broader network.

5. Seismic activity in Year 11

5.1 Earthquakes located for 1999

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 1999 published and distributed in April 2000 (Walker, 2000). A map of the 147 events located in 1999 is reproduced here as Figure 11 and a catalogue of the 27 with magnitudes of 2.0 or greater is given in Annex B. Twelve in that magnitude category, together with 21 smaller ones, are known to have been felt.

Spatially, the distribution of seismicity in 1999 was similar to that of 1998 with the majority of earthquakes occurring near the tip of Cornwall, in Wales, the Midlands, the Borders, and in central and western Scotland. There was also some continued activity around the Channel Islands. There were no events in southwest Wales and the Bristol Channel area, or in the English Channel, which were all active in 1998. Some earthquakes were located in regions that have previously experienced few instrumentally located earthquakes, for example, the very north of Ireland, the Orkney and Shetland Islands. The southeast of England continued to be aseismic in 1999, along with the rest of Ireland, the Irish sea, northeast England, northern Scotland, central and eastern Scotland, and the outer Hebrides. Historically, however, southeast England has been active both instrumentally and historically, unlike Ireland, northern Scotland, and central and eastern Scotland, which have had few previous events. Earthquake occurrence during 1999 was fairly uniform throughout the year, with a few locations experiencing several small events within a short period of time (4-7 events). These occurred near Dumfries (February-March), Betws-y-Coed, North Wales (July) and Jura (November). There were no large swarms which have often characterised UK seismicity in the past. The largest event in 1999 was the Arran earthquake, with a magnitude of 4.0 ML, which was followed by two small aftershocks (discussed in more detail in the 10th Annual report and the 1999 Bulletin of British Earthquakes).

In the period since BGS extended its modern seismic monitoring in the UK (1979 to March 2000), 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.

5.2 Significant events

Highlights of the seismic activity during the eleventh year of the project (April 1999 to March 2000) are given below:

(i) On 15 April, an earthquake, with a magnitude of 2.9 ML, occurred near Mallaig, Highland. It was felt in Arnisdale, Loch Hourn and Glen Garry, with intensities of at least 3 EMS in the epicentral area. Felt reports described "a dull progressive rumbling" and "felt a shaking". This is the largest event to have affected the area since the 30 January 1986 earthquake (magnitude 3.0 ML) which was also felt with intensities of at least 3 EMS.

(ii) Near Aviemore, Highland, an earthquake, with a magnitude of 2.2 ML, occurred on 29 May. Felt reports were received from residents of Boat of Garten, where intensities reached at least 3 EMS in the epicentral area. Felt reports described "the house shook" and "heard a loud bang". This event locates in the same area as the magnitude 2.7 ML Aviemore earthquake which occurred in 1995 and which was felt throughout the region with maximum intensities of 4 EMS.

(iii) An earthquake occurred near Hereford on 17 June, with a magnitude of 2.8 ML. Felt reports were received from residents of Cradley and Welland, where intensities reached at least 3 EMS in the epicentral area. A single report was received from a resident in Cradley (who was awake at the time), some 18 km northeast of the epicentre, who reported "the whole cottage shook like a heavy lorry passing outside" and "the dressing table rattled". This event was recorded on the strong motion instrument near Hereford, some 33 km away, where accelerations of 8, 20 and 12 mms^{-2} were measured for the vertical, NS and EW components, respectively (Fig. 13). A focal mechanism for the event was calculated using data from stations up to 169 km away and shows dominant normal faulting with a component of strike-slip motion. The area has been seismically active in the past with earthquakes of 5.2 and 5.3 occurring in 1863 and 1896, respectively. These events were felt over most of England and Wales and caused damage in the epicentral area (Musson, 1994).

(iv) An earthquake, with a magnitude of 1.8 ML, occurred 6 km west of Jersey, Channel Islands on 13 July. Thirty five felt reports were received via colleagues at Jersey Airport, who had been contacted by residents throughout the west side of the island. Felt reports described "heard a loud noise", "the walls and roof rattled", "the house shook" and "the window and cooker shook". The event locates approximately 5 km north west of the felt earthquake on 22 June 1997, which had a magnitude of 2.2 ML.

(v) Near Loch Earn, an earthquake, with a magnitude of 2.0 ML, occurred on 19 July. Felt reports were received from residents of the village of St Fillans, where intensities reached at least 3 EMS. Felt reports described “the building shook violently” and “felt like a car crashing into the side of the house”. This is the first earthquake to be reported felt in the immediate area and is the largest to be located in the general area since the 26 November 1975 Glen Almond earthquake which had a magnitude of 2.4 ML.

(vi) A magnitude 3.1 ML earthquake occurred near Caernarvon, Gwynedd, on 1 September. It was felt as far away as Barmouth, 60 km to the south, and in Rhyl, 55 km to the east. Felt reports described “the whole house vibrated” and “heard loud rumblings and vibrations”. This earthquake was followed by a magnitude 1.2 ML aftershock, which was reported felt in the Llangefni area. A macroseismic survey was conducted for the main event and over 100 replies were received, giving a maximum intensity of 4 EMS. The event locates some 7 km northeast of the Caernarvon Bay earthquake which occurred on 29 July 1992, was felt over 10,000 km^2 and had a magnitude of 3.5 ML. A seismogram of the event recorded on the Hereford network is shown in Figure 14.

(vii) Two felt earthquakes with magnitudes of 2.1 and 1.3 ML, occurred in the Johnstonebridge area of Dumfries and Galloway, with intensities of 3 and 2 EMS, respectively, on 3 September. Felt reports described “like an explosion” and “heard a loud rumble”. The area around Johnstonebridge has been seismically active for a number of years with most of the swarm activity occurring to the west of these events.

(viii) On 29 September, an earthquake with a magnitude of 3.0 ML, was located 370 km WSW of the Faroe Islands, in the North Atlantic. It was located using data from the recently installed station in the Faroe Islands (FTO), two Icelandic stations and the northern Scotland networks.

(ix) The largest earthquake of the year, with a magnitude of 3.6 ML, occurred near Sennybridge, Powys, on 25 October. Felt reports described “everybody came running out into the street”, “the whole house shook” and “felt like an explosion”. A macroseismic survey was conducted and around 270 replies were received, giving a maximum intensity of 5 EMS (Plate 4). A focal mechanism for the Sennybridge earthquake shows dominant normal faulting with a varying component of strike-slip motion. Two weeks after the event, a small aftershock, with a magnitude of 1.9 ML was located in the same area. In the past thirty years, the area has experienced a number of small earthquakes (up to 2.6 ML) but, historically, it has been affected by large earthquakes with magnitudes over 5.0 ML. They occurred near Swansea some 40 km to the southwest in 1727, 1775 and 1906, caused damage in the epicentral area and were felt up to 200 km away. A seismogram of the earthquake recorded on the North Wales network is shown in Figure 15. The earthquake was recorded on the strong motion instrument at Bonnylands (HBL2), some 38 km away, where accelerations of 19.8, 37.7 and 10.8 mms^{-2} were measured for the vertical, NS and EW components, respectively (Fig. 16).

(x) On 22 November, an earthquake with a magnitude of 2.7 ML, occurred on Jura, Strathclyde. Felt reports described “sounded like a long rumble” and “the house shook”.

It was followed by a magnitude 1.8 event on the same day and two more aftershocks on 3 December with magnitudes of 2.2 and 1.8 ML. Two other small earthquakes occurred before these, in September, with magnitudes of 1.7 and 1.5 ML; none of these were felt. The mainshock locates approximately 20 km southeast of the magnitude 3.5 ML Jura earthquake on 3 May 1998, which was felt with intensities of 4 EMS in the epicentral area. Two further Jura events occurred on 3 December in the same area, with magnitudes of 2.2 and 1.8 ML; no felt reports were received for either of these events. Offshore Jura, two events with magnitudes of 1.7 and 1.5 ML occurred on 4 and 15 September, respectively. No felt reports were received.

(xi) Near Altrincham, Greater Manchester, an earthquake, with a magnitude of 2.8 ML occurred on 14 December. Earthquakes of this size are usually felt when they occur onshore but enquiries to Manchester Police, revealed that no felt reports were received. The time of day (09:43 UTC) and the location, which is close to a motorway and Manchester Airport, probably contributed to the lack of felt effects at the surface.

(xii) 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 of 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, it is the largest event since the magnitude 3.5 ML Lochgilphead earthquake in 1972, some 20 km to the northeast, which was felt with intensities of at least 4 EMS. A seismogram of the event recorded on the Paisley network is shown in Figure 17.

(xiii) 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 were felt with intensities of at least 4 EMS. A seismogram of the event recorded on the Lowlands network is shown in Figure 18.

(xiv) Six events, with magnitudes ranging between 0.9 and 1.8 ML, occurred near, Dumfries and Galloway. Two of these events were felt by local residents in Tinwald some 6 km from the epicentre. Felt reports described “slight shaking” and “like an explosion” indicating an intensity of at least 3 EMS.

(xv) Five earthquakes were detected in the Blackford area of Tayside during the reporting year, with magnitudes ranging between 0.7 and 1.9 ML. This is an area that has continued to be active. In 1979, the magnitude 3.2 ML Ochil Hills earthquake, in this area, was felt with a maximum intensity of 5 EMS.

(xvi) In North Wales, 3 events, with magnitudes of –0.2, 0.1 and 1.2 ML, were located on the Lleyn Peninsula, in the same area and at similar depths as the magnitude 5.4 ML Lleyn earthquake of 19 July 1984, which was felt throughout England and Wales and into Scotland and Ireland.

(xvii) Near Newcastle-under-Lyme, Staffordshire, three shallow events (3-4 km) occurred, with magnitudes of 1.7, 2.4 and 2.6 ML. The two largest being felt by local residents in the Keele area of Staffordshire. They are not believed to be associated with mining in the area.

(xviii) The coalfield areas of central Scotland, Yorkshire, Nottinghamshire and Mid Glamorgan continued to experience earthquake activity of a shallow nature which is believed to be mining induced. Some 17 coalfield events, with magnitudes ranging between 0.5 and 2.1 ML, were detected in the year. Six of these were reported felt by local residents. Five events, with magnitudes ranging between 0.5 and 1.4 ML, were located near Clackmannan in the central region of Scotland; three were reported felt. This is an area which has experienced many such mining induced events in the past.

(xix) Near Mansfield, Nottinghamshire, four coalfield events were located with magnitudes ranging between 0.8 and 2.1 ML. Two were felt by the local population. A seismogram of the largest event is shown in Figure 19.

(xx) Near Bargoed, Mid Glamorgan, three events with magnitudes of 0.9 ML, 1.9 ML and 1.4 ML, occurred; the largest was felt in Blackwood with intensities of at least 3 EMS. They are shallow and are thought to be the result of previous mining in the area. Four other events have occurred in the area in July and August, but these are thought to be natural owing to their depth of occurrence (6.4-7.4 km).

(xxi) In other coalfield areas, small events were located near Sheffield, South Yorkshire (1.0 ML, 30 May 1999), Rotherham, South Yorkshire (1.3 ML, 30 June 1999), Ollerton, Nottinghamshire (1.0 ML, 23 July 1999), Papplewick, Nottinghamshire (1.3 ML, 24 December 1999; felt in Papplewick), Newark-on-Trent, Nottinghamshire (1.1 ML, 14 February 2000). These events are probably related to present-day coal mining activity.

(xxii) Elsewhere in the country, many seismic events have been reported felt or heard like small earthquakes but, on analysis, have been proved to be sonic booms (Fig. 20). Specific examples are: Mid Glamorgan (16 May 1999), Isle of Lewis (30 July 1999), Cumbria (7 September 1999), Lincolnshire (22 November 1999), North Norfolk (2 December 1999) and Grampian (20 January 2000).

(xxiii) Reports have been received of other man-made events. A world war two mine was detonated in the English Channel on 6 October 1999. It had a magnitude of 3.2 ML and represents the largest recorded explosion since a major controlled explosion experiment in 1974 in which events up to magnitude 3.8 ML were detonated. A seismogram of the event recorded on the Jersey network is shown in Figure 21. Over 100 explosions were detonated near Weston Super Mare in summer 1999 and March 2000, some of which were felt by the local population. A typical seismogram is shown in Figure 22.

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 seen a number of significant and devastating earthquakes, details of which are given below.

(i) The largest and most disastrous earthquake during the year, with a magnitude of 7.5 Ms, occurred on 17 August in NW Turkey (Plate 5). It killed some 17,100 people (78% of the global fatalities from earthquakes in 1999), injured over 44,000, and damaged or destroyed over 350,000 buildings. The epicentre of the earthquake was 11 km SE of the industrial city of Izmit, which has a population of over one million. Most of the damage and fatalities occurred in Izmit and Gölcük but a much larger area, including Istanbul, was also affected. The earthquake occurred on the northern part of the North Anatolian Fault system at a depth of about 17 km. The mechanism was right-lateral strike-slip and the movement produced 60 km of surface rupture and offsets of up to 2.7 metres. A seismogram of the event recorded on the Lowlands network is shown in Figure 23. The earthquake attracted high media interest and was CNN's fourth top news story of the year. BGS were cited in connection with the story. A second fatal and damaging earthquake, with a magnitude of 7.5 Ms, occurred approximately 100 km east of the 17 August event, in November, near the city of Düzce (Plate 6). It killed over 840 people, injured almost 5,000 more and caused extensive damage in the Ankara-Istanbul-Kaynasli area. Several other significant events occurred in the northern Turkey area during the year causing the deaths of a further 11 people, injury to hundreds more and additional damage to Izmit and Düzce.

(ii) In Athens, Greece, on 7 September, a magnitude 5.8 Ms earthquake killed 143 people, injured thousands more and completely or partially damaged over 74,000 homes affecting over 200,000 people (Plate 7). The areas that suffered most destruction were the relatively poorer suburbs of Athens, some of which include Menidi, Ano Liosia, Thracomacedones, Philadelfia, Metamorphosi, Ilion and Galatsi. It was felt throughout most of central Greece, as far away as Corinth, 100 km to the south, and was also felt in parts of Turkey. Damage, as a result of this earthquake, has been estimated at US$655 million.

(iii) On 20 September, an earthquake with a magnitude of 7.6 Ms, occurred near the town of Chi-Chi in Nantou County, central Taiwan, approximately 150 km south of Taipei (Plate 8). It killed at least 2,400 people, injured some 10,000 more and caused damage to over 82,000 housing units, leaving around 300,000 people homeless. The most affected areas were Nantou and Taichung counties. A seismogram of the earthquake recorded on the Lowlands network is shown in Figure 24. Two more earthquakes in the area on 25 September (magnitude 6.4 Ms) and 22 October (magnitude 5.6 Ms), caused further damage and additional casualties. The cost of the damage for the earthquakes in Taiwan is estimated at US$14 billion. Five earthquakes of similar destructive potential as this one have occurred on the west coast of Taiwan in the past 150 years; a magnitude 6.5 event in 1848 killing 1000, a magnitude 6.5 event in 1862 killing 1000, a magnitude 7.0 event in 1906 killing 1276 and a magnitude 7.1 event in 1935 killing over 3200, with a magnitude 6.5 aftershock which killed over 2700. Most of Taiwan's seismicity is concentrated on or offshore the east coast where the population density is much lower.

6. The National Seismological Archive (NSA)

6.1 Identification, curation and cataloguing

The series of eight reports detailing the principal NSA material, together with that relating to John Milne, has been completed with the publication of two reports, which are listed in Annexes F and G.

One of the major duties of the archive is the presentation of current knowledge of UK historical earthquake seismology material. This has been achieved by making the series of eight reports easily accessible to researchers. These are available for download or online reading as Adobe Acrobat Portable Document Format files (.pdf) from the web page, which lists each report with a brief description (http://www.gsrg.nmh.ac.uk/hazard/nsa_reports.htm).

In addition to web access, more coherent links with the BGS library information system have been discussed with Bob McIntosh, the BGS Edinburgh librarian. This would result in the NSA database being integrated into the new library GEOLIB system, expanding accessibility.

The NSA holds at least 35,000 original questionnaires detailing earthquake felt effects, collected by the BGS since about 1974. These have now been microfilmed for data preservation.

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 now 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.

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. Two seismograms have been discovered on the Isle of Wight, amongst Milne material.

Rathfarnham: Material from the Rathfarnham Castle Observatory, Dublin (1916-1964), are 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).

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.

6.2 Storage and Inspection facilities

The National Seismological Archive has been visited this year by four researchers, and data requests and enquiries have been answered from scientists and researchers world-wide.

Archive material has been supplied to and received from 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. This will continue in 2000-2001.

The NSA Internet Web pages have been thoroughly revised, with reports available for reading online or for download, database search page and descriptions of the main collections (address 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 42 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 Caernarvon and Sennybridge earthquakes were 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 132,000 visits have been logged, an increase of over 160% on 1999.

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 1999, it was issued within 3 months.

8. Programme for 2000/01

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, as opportunities arise, further strong motion and broad band instruments will be installed. Specific advances anticipated for 2000/01, 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) 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.

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 Director of the British Geological Survey (NERC).

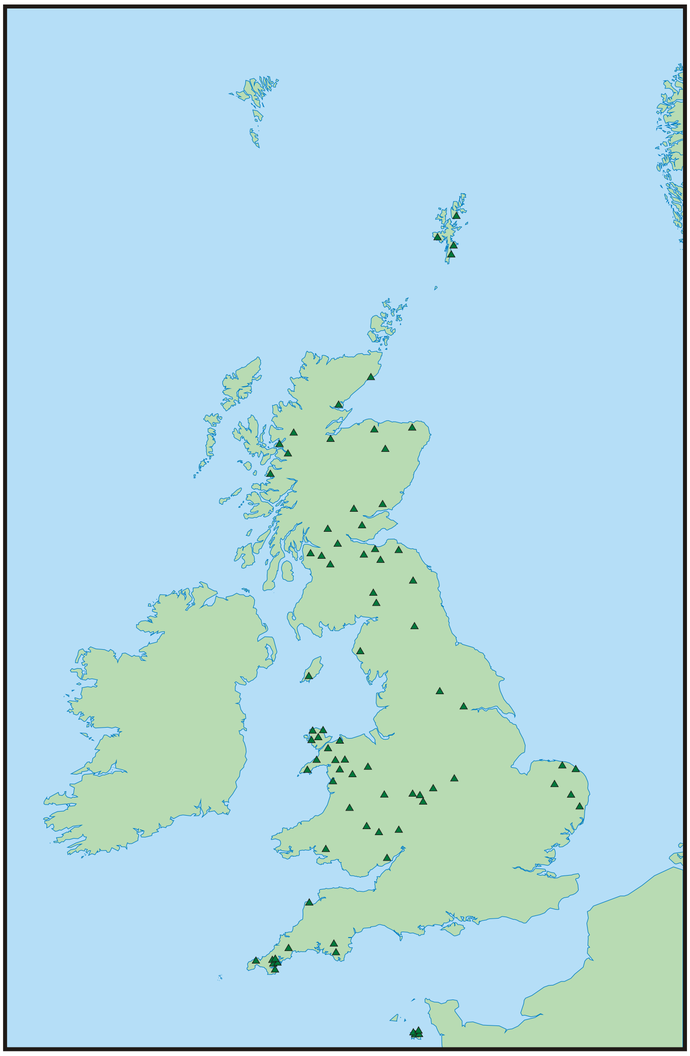
10. References

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

Walker, A.B. (editor), 2000. Bulletin of British earthquakes 1999, Brit.Geol.Surv. Tech. Rep. No. WL/00/01.

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.

Figure 1. BGS rapid access seismograph network operational March 2000.



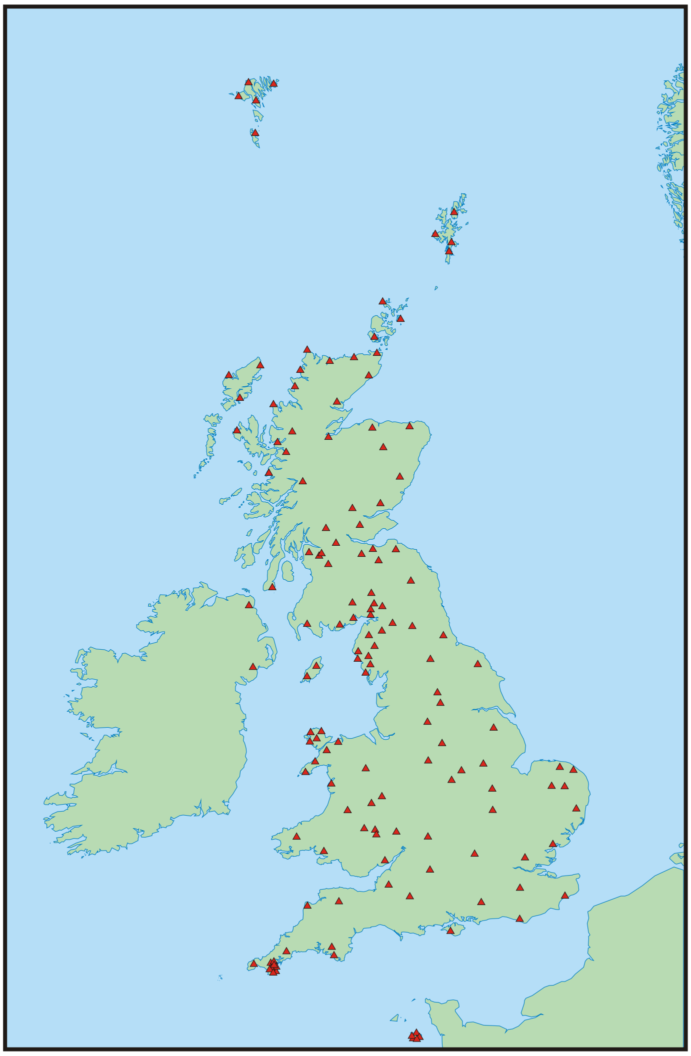


Figure 2. BGS seismograph network in 1988 prior to the commencement of the UK monitoring enhancement project.

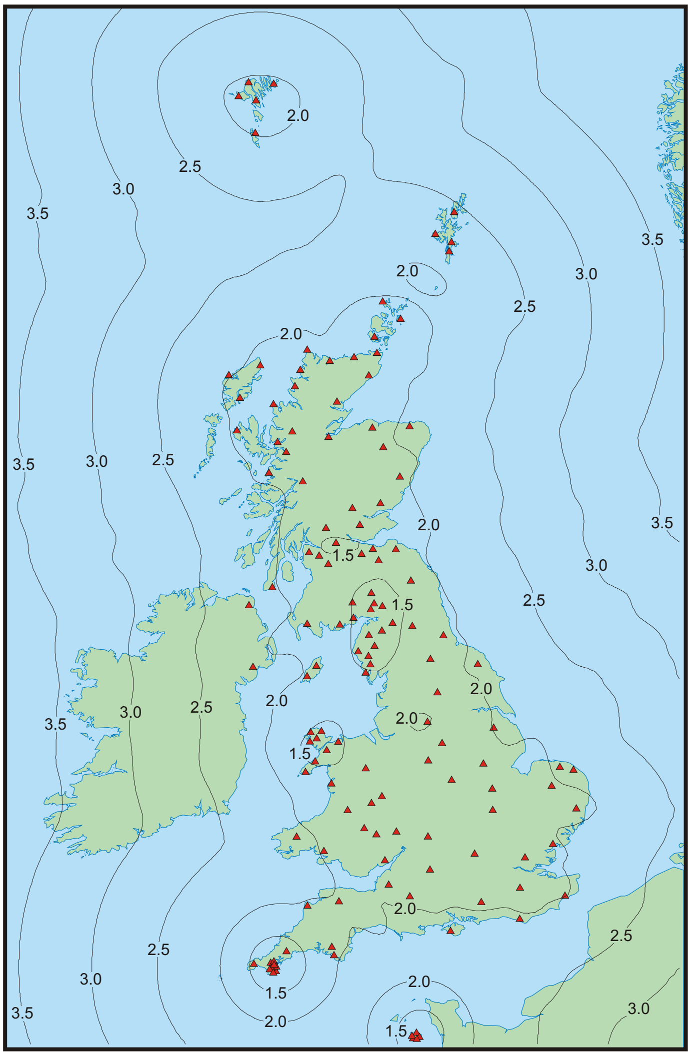


Figure 3. Detection capability of network, March 2000. Contour values are Richter local magnitude (ML) for 20 nanometres of noise and S-wave amplitude twice that at the fifth nearest station.

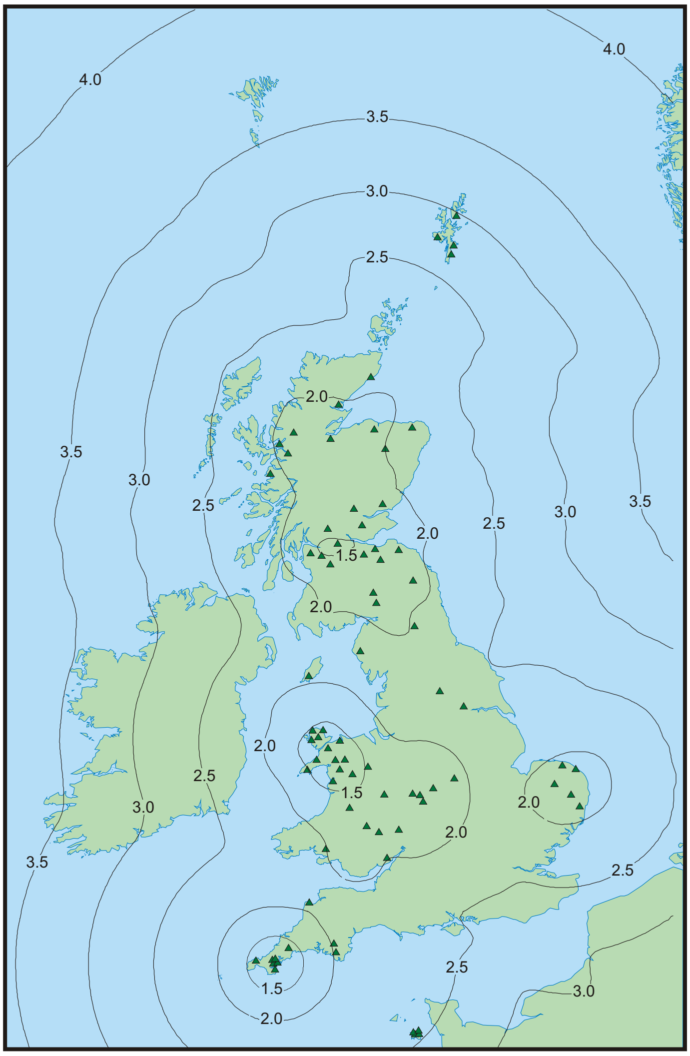


Figure 4. Detection capability of network, 1988. Contour values are Richter local magnitude (ML) for 20 nanometres of noise and S-wave amplitude twice that at the fifth nearest station.

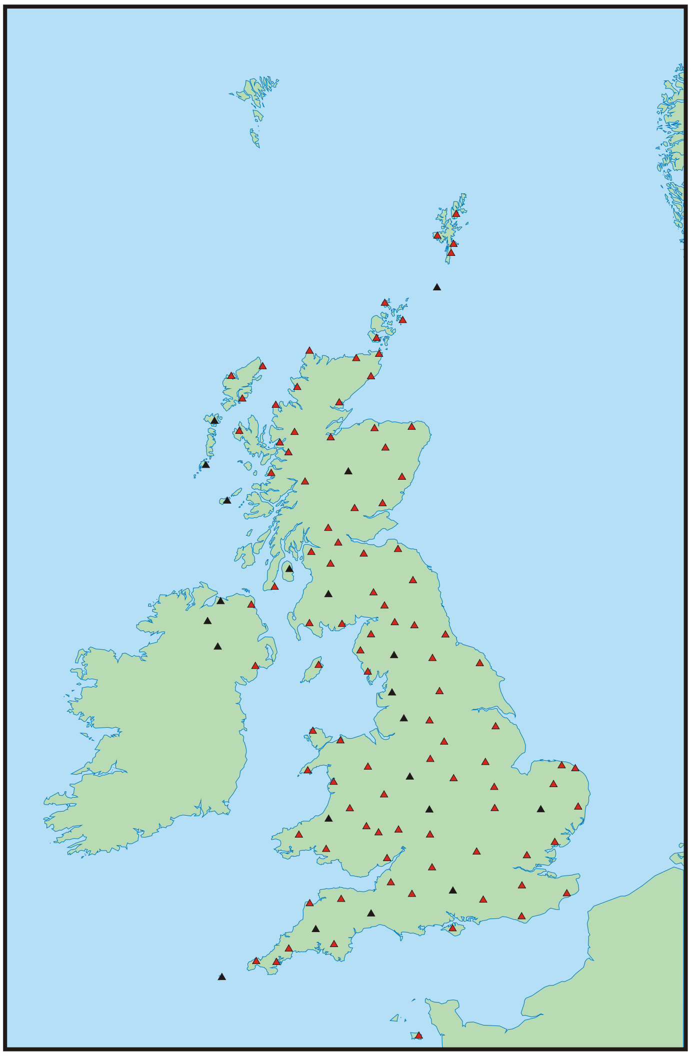


Figure 5. Proposed long-term background seismic monitoring network with an average station spacing of 70 km. Colour coding shows existing coverage (red) and proposed stations (black).

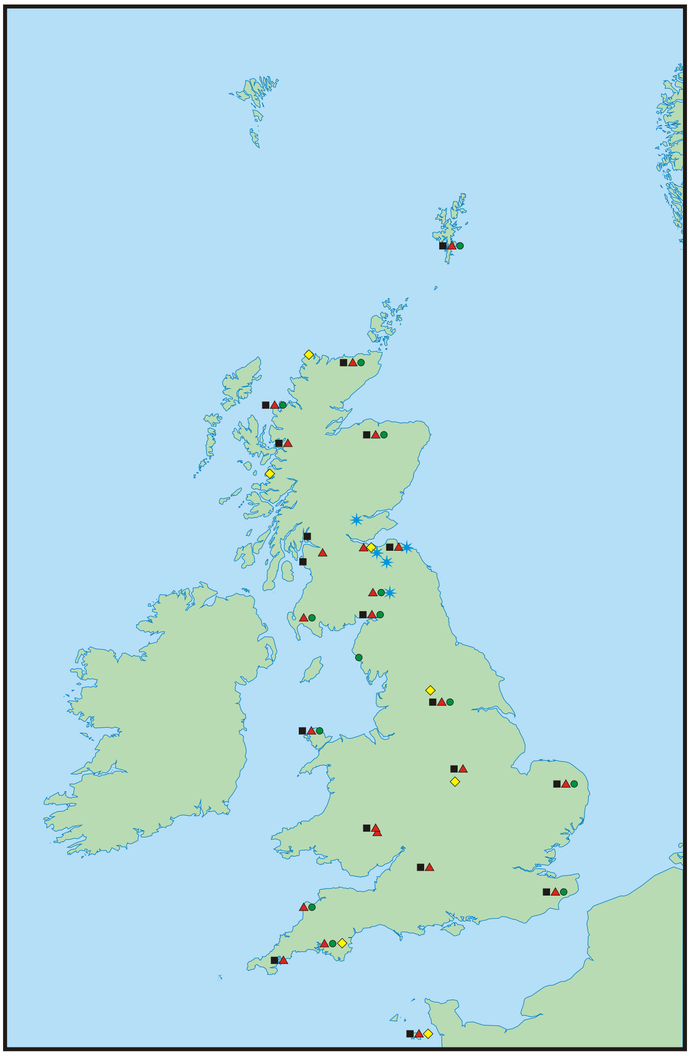


Figure 6. BGS network of strong motion instruments (black), low sensitivity (red), broadband (yellow), microphones (green) and environmental stations (blue) in March 2000.

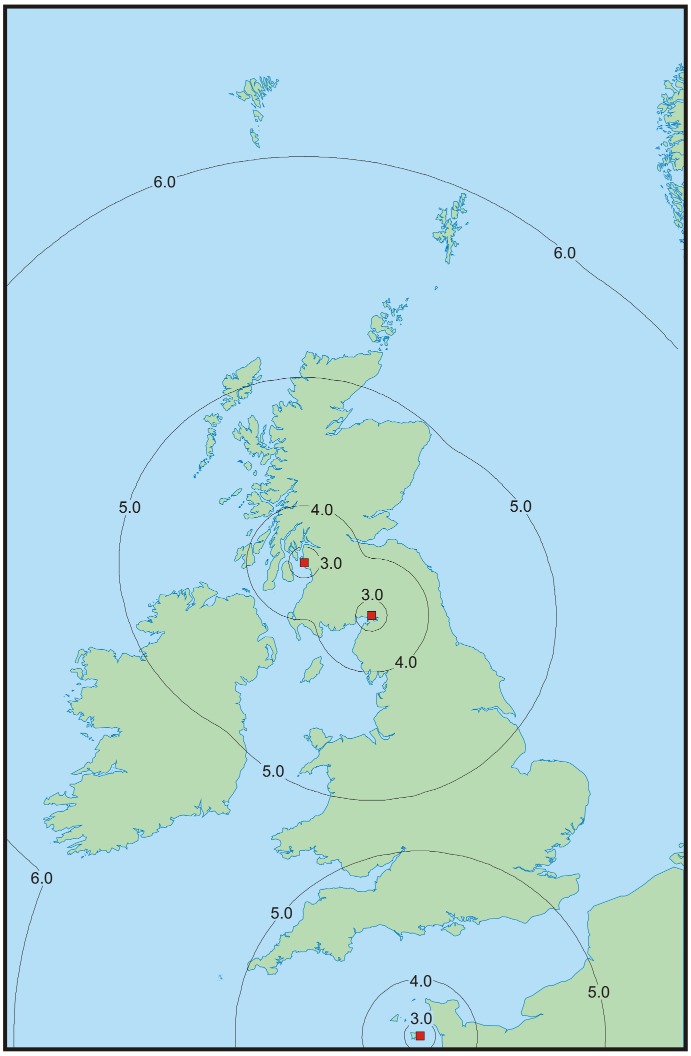


Figure 7. Minimum Richter local magnitude (ML) detectable by the strong motion network operational December 1992.

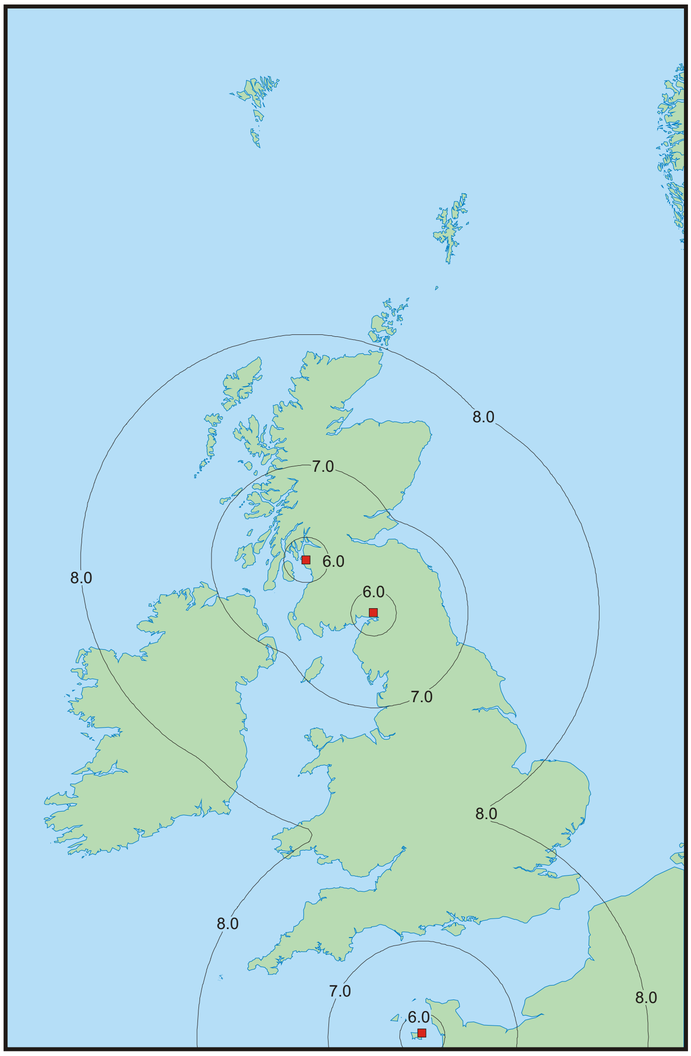


Figure 8. Maximum Richter local magnitude (ML) measurable by the strong motion network operational December 1992.

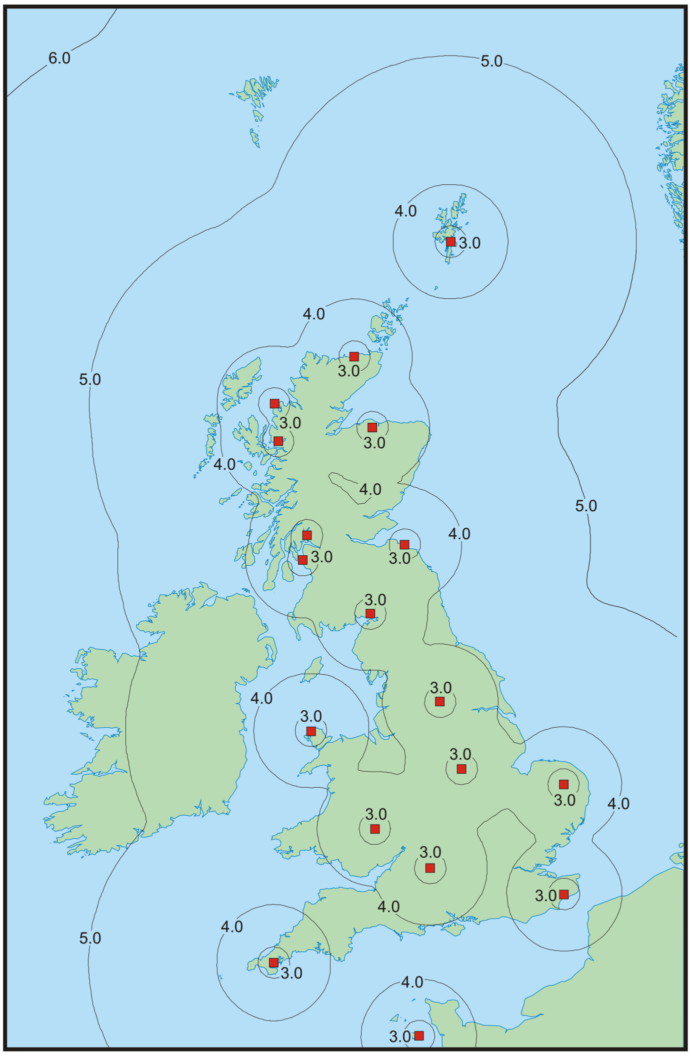


Figure 9. Minimum Richter local magnitude (ML) detectable by the strong motion network operational March 2000.

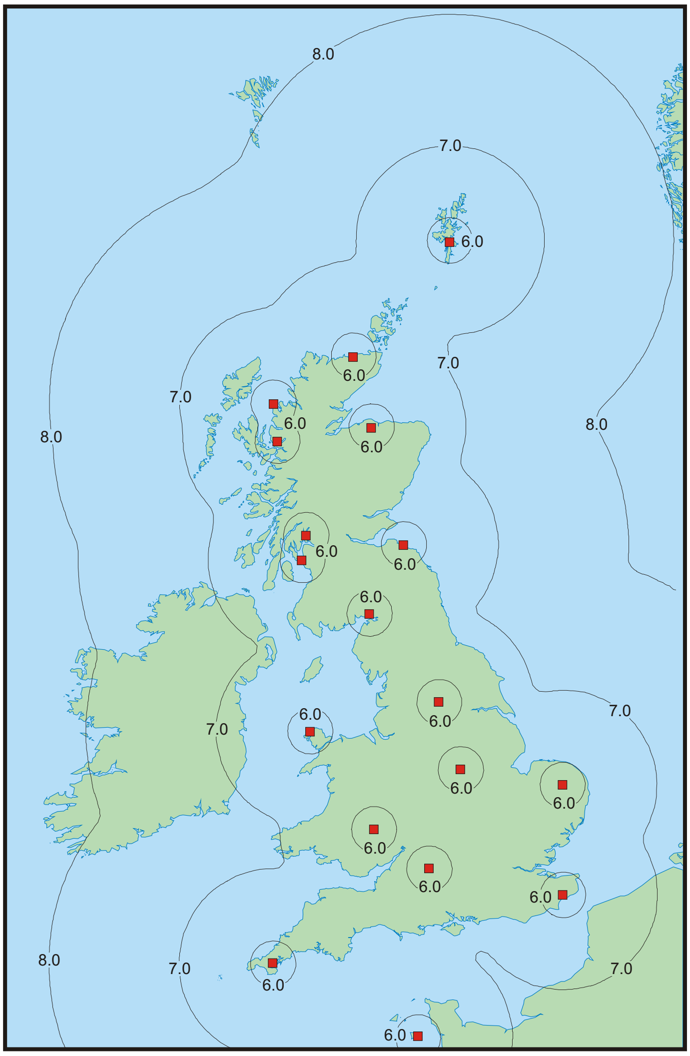


Figure 10. Maximum Richter local magnitude (ML) measurable by the strong motion network operational March 2000.

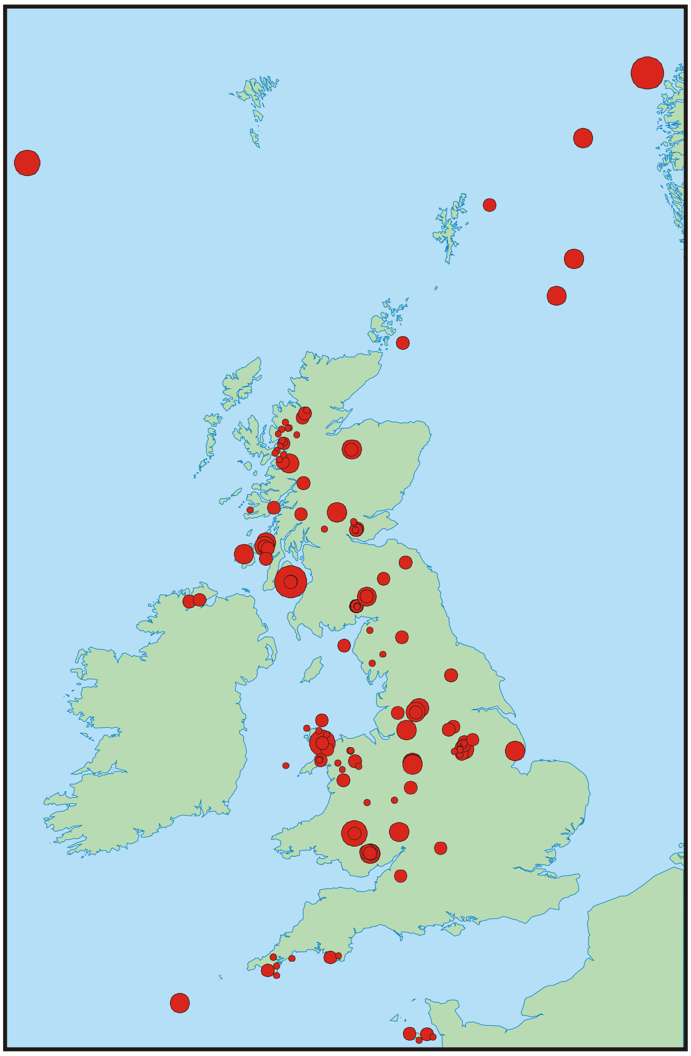
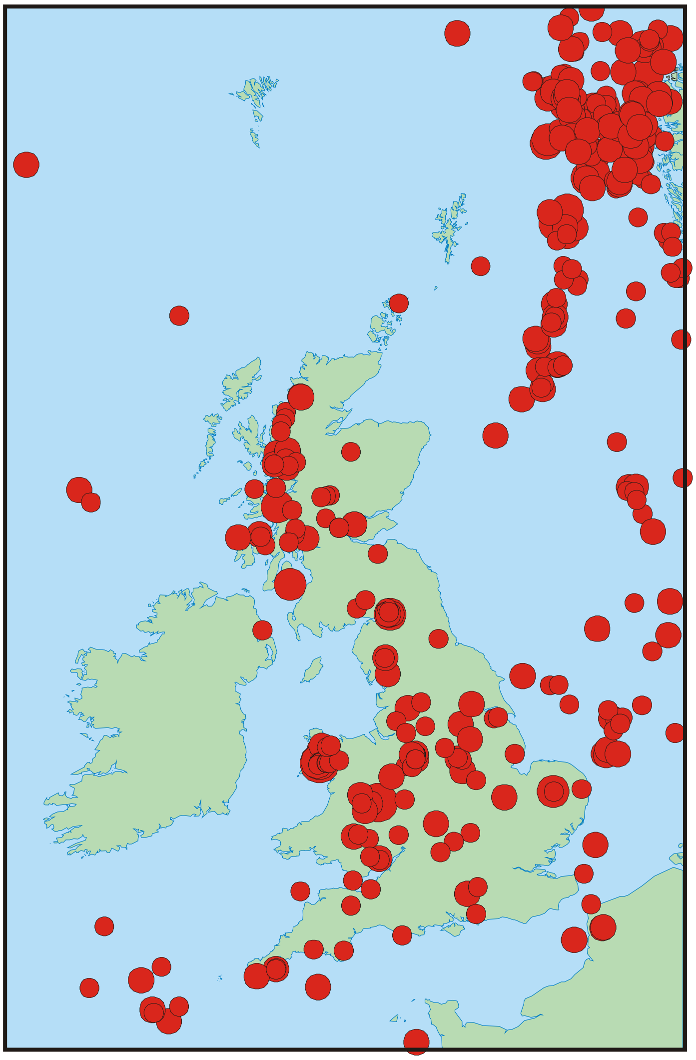


Figure 12. Epicentres of earthquakes with magnitudes 2.5 ML or greater, for the period 1979 to March 2000.

Figure 11. Epicentres of all UK earthquakes located in 1999.



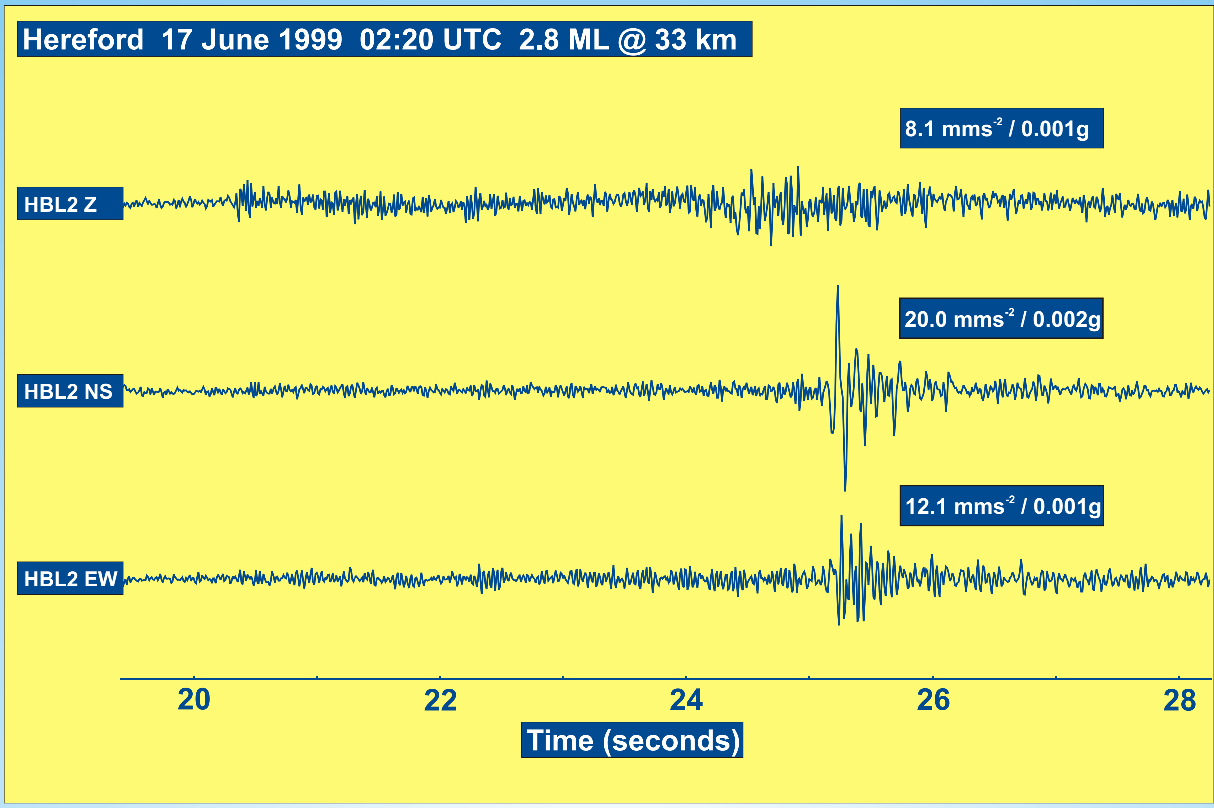


Figure 13. Seismograms recorded on the strong motion instruments near Hereford from the Hereford earthquake with a magnitude of 2.8 ML on 17 June 1999 02:20 UTC. Three letter codes refer to stations in Annex E.

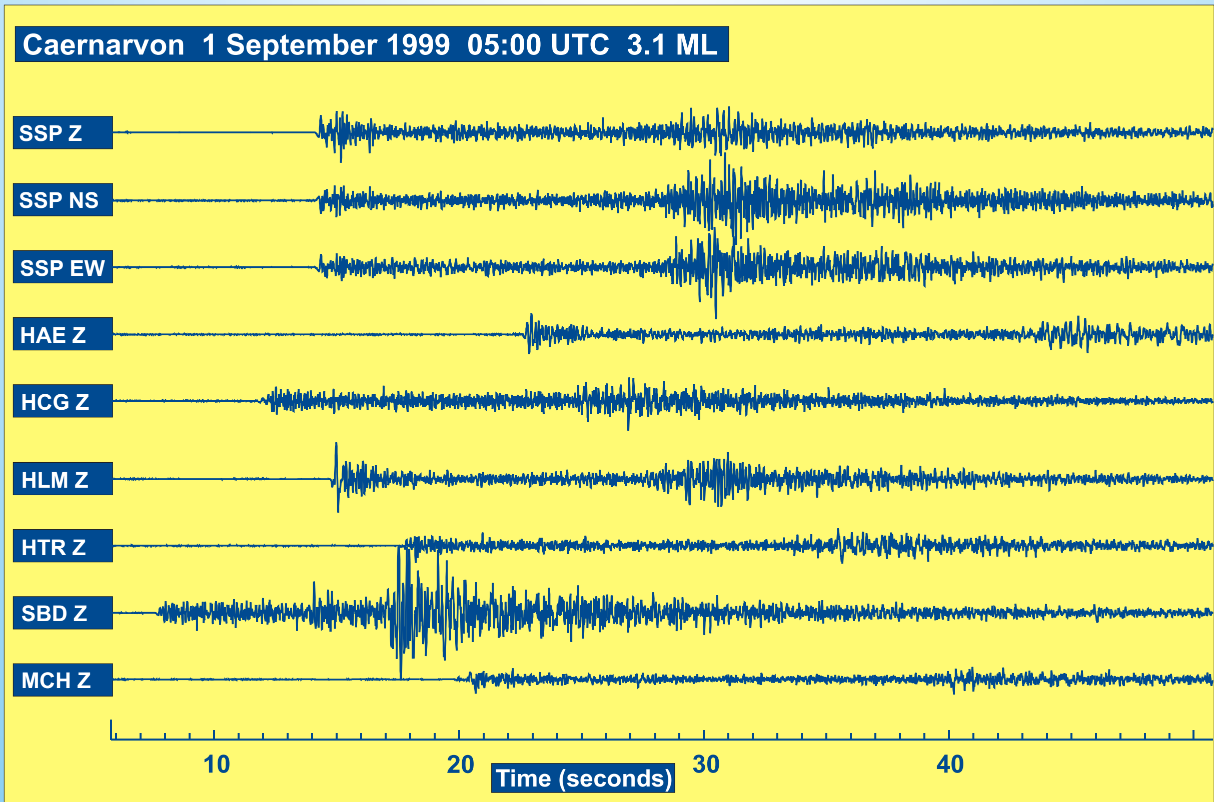


Figure 14. Seismograms recorded on the Hereford network from the magnitude 3.1 ML earthquake felt in the Gwynedd area on 1 September 1999 05:00 UTC. Three letter codes refer to stations in Annex E.

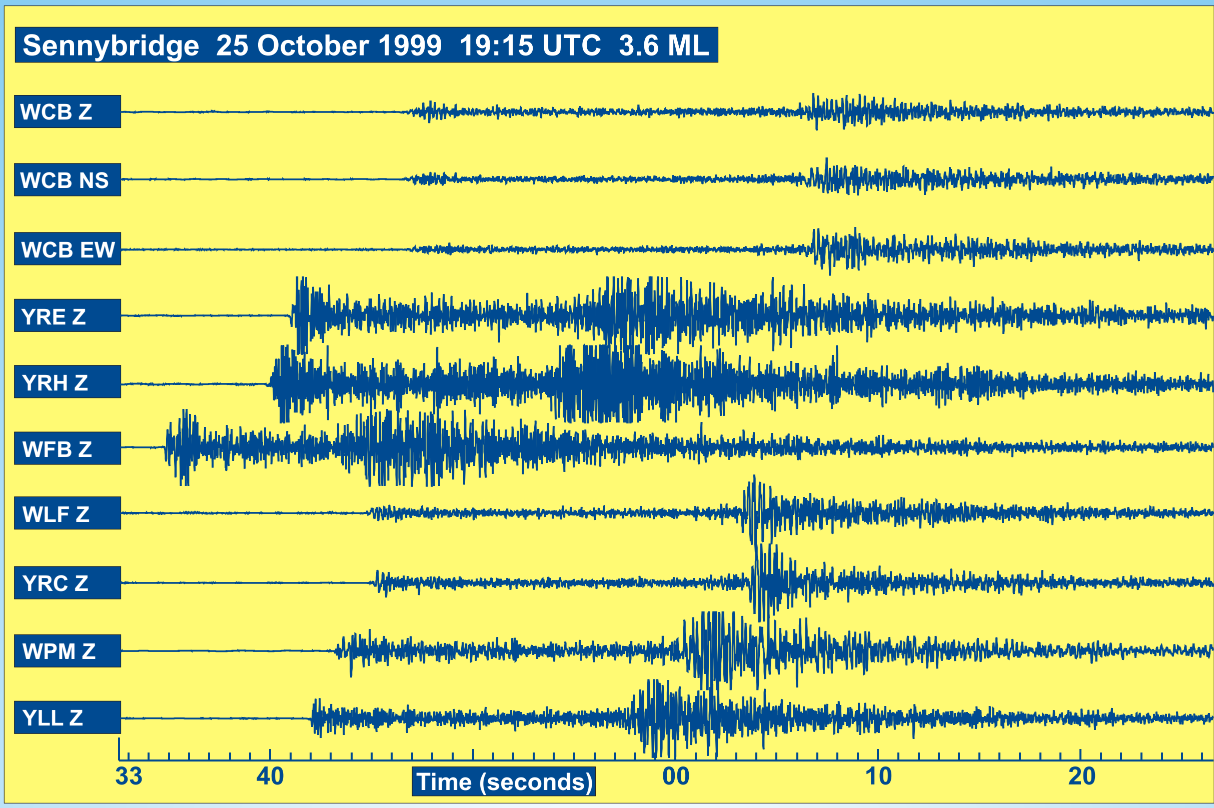


Figure 15. Seismograms recorded on the North Wales network from the magnitude 3.6 ML earthquake felt in the Powys area on 25 October 1999 19:15 UTC. Three letter codes refer to stations in Annex E.

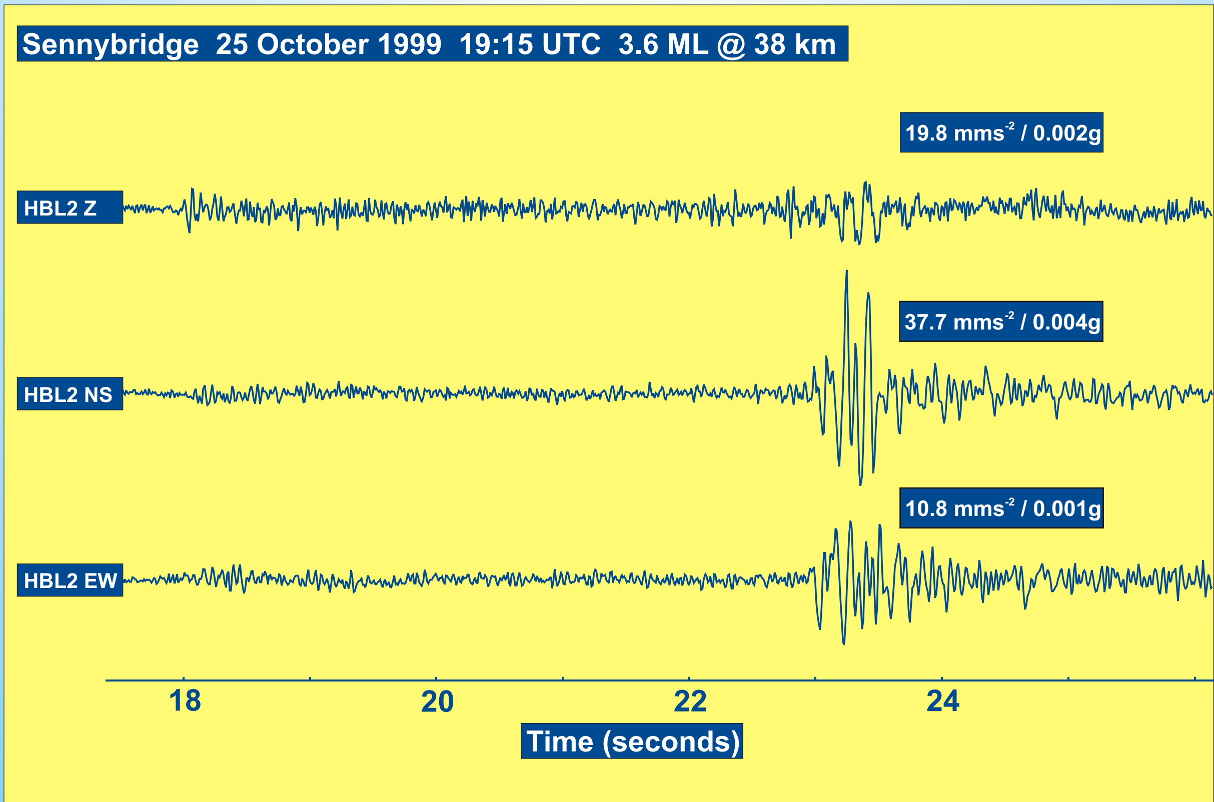


Figure 16. Seismograms recorded on the strong motion instruments near Hereford from the Sennybridge earthquake with a magnitude of 3.6 ML on 25 October 1999 19:15 UTC. Three letter codes refer to stations in Annex E.

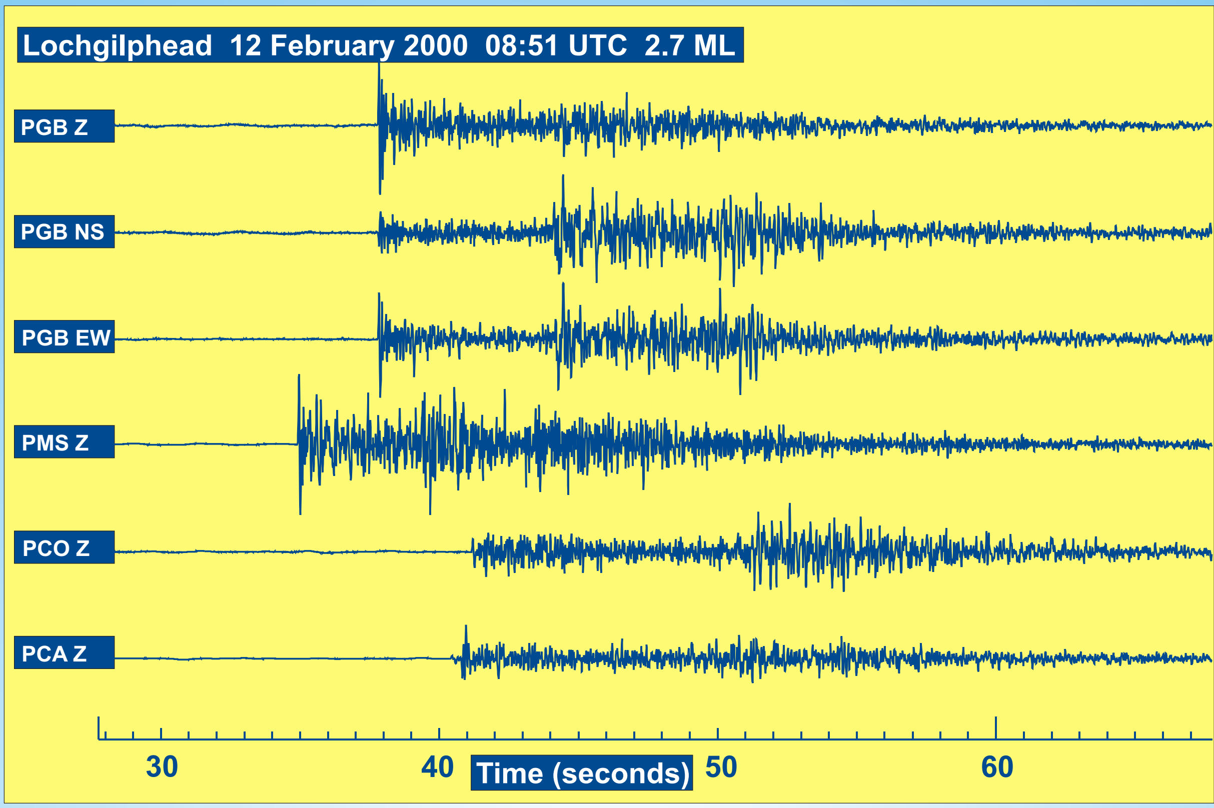


Figure 17. Seismograms recorded on the Paisley network from the magnitude 2.7 ML earthquake felt in the Strathclyde area on 12 February 2000 08:51 UTC. Three letter codes refer to stations in Annex E.

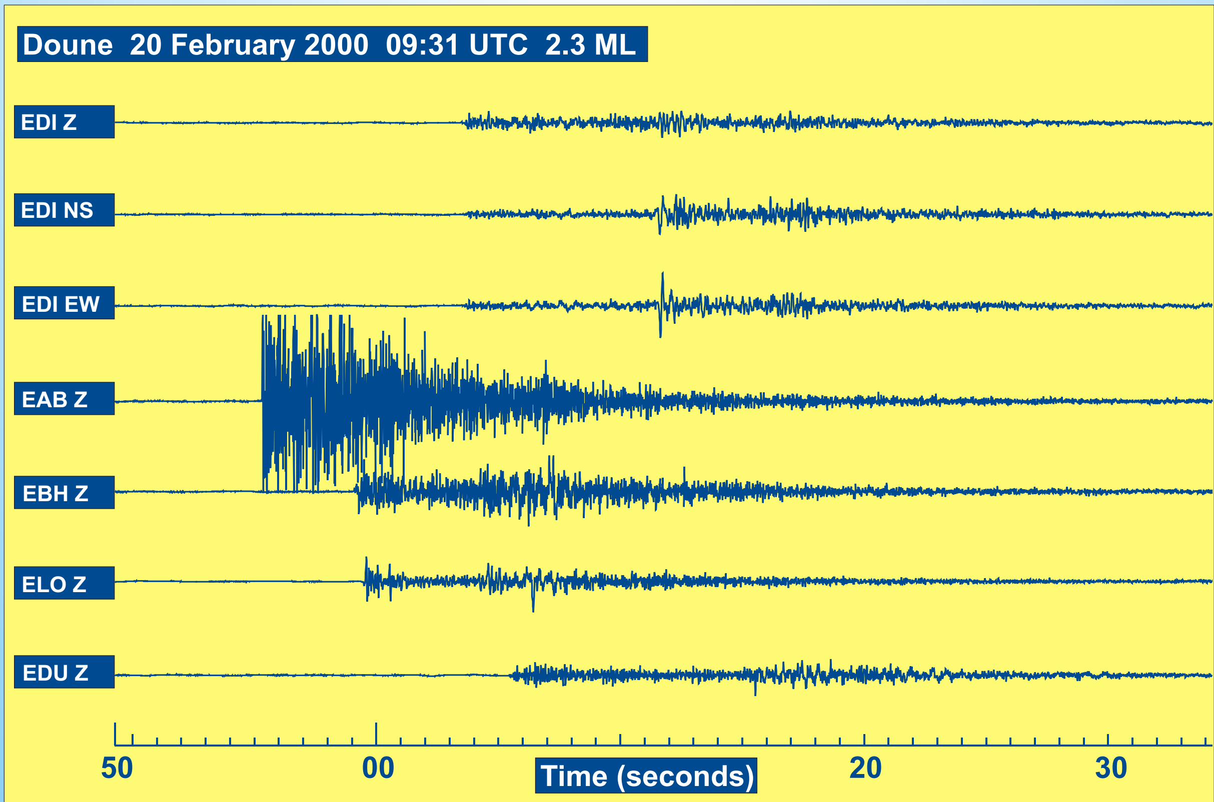


Figure 18. Seismograms recorded on the LOWNET network from the magnitude 2.3 ML earthquake felt in the Doune area on 20 February 2000 09:31 UTC. Three letter codes refer to stations in Annex E.

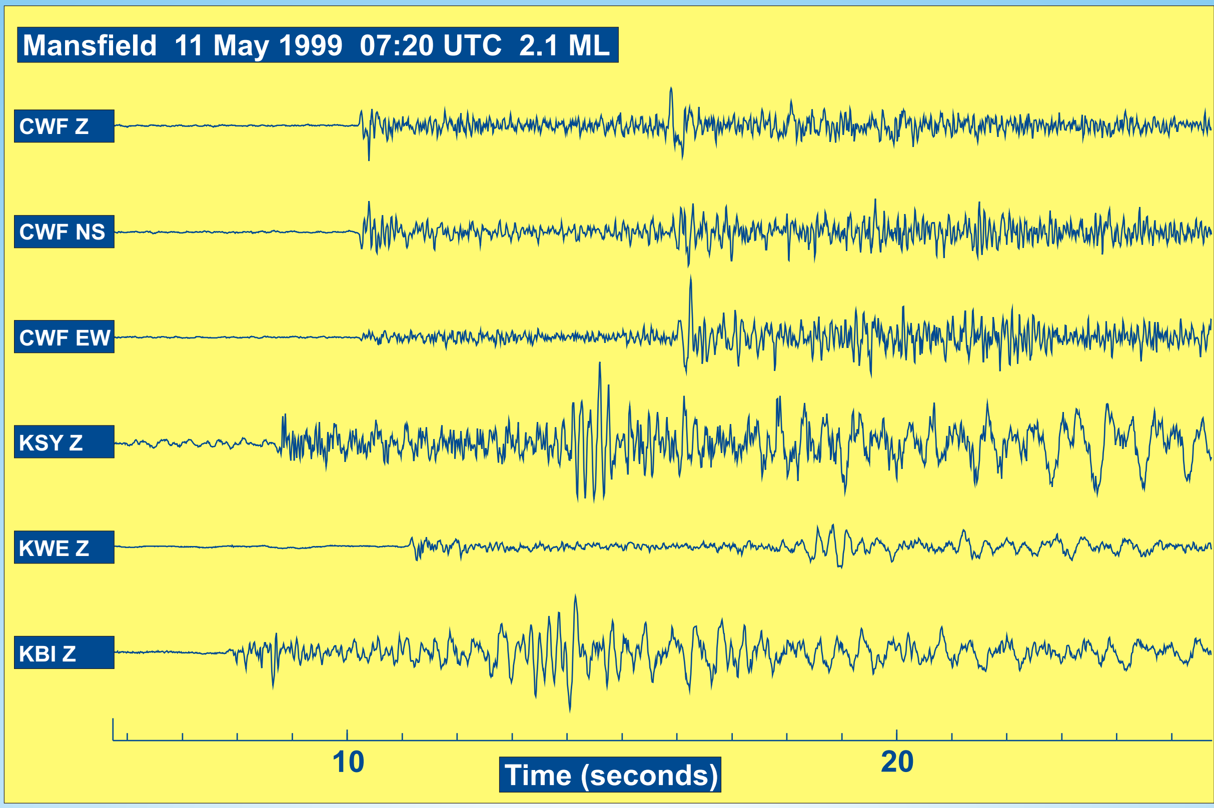


Figure 19. Seismograms recorded on the Keyworth network from the magnitude 2.1 ML coalfield event in the Mansfield area on 11 May 1999 07:20 UTC. Three letter codes refer to stations in Annex E.

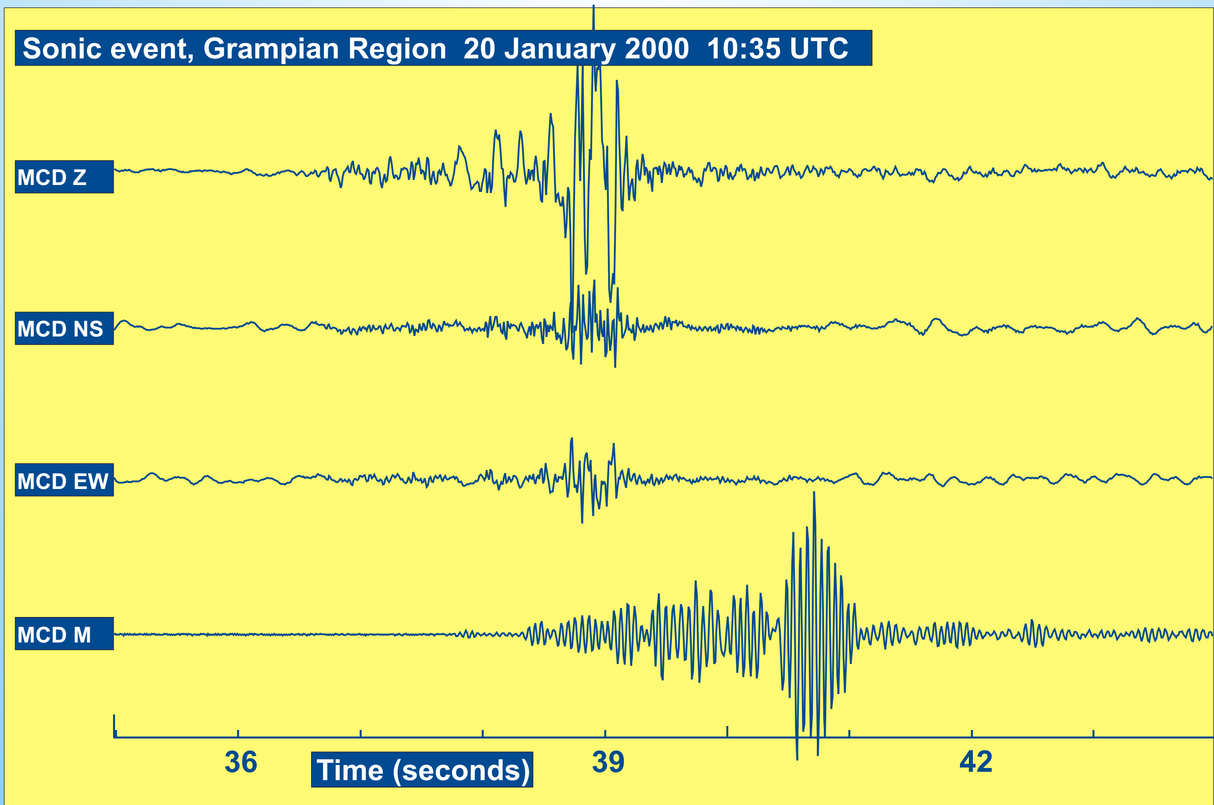


Figure 20. Seismograms recorded on the Moray network from the sonic event felt in the Grampian area on 20 January 2000 10:35 UTC. Three letter codes refer to stations in Annex E.

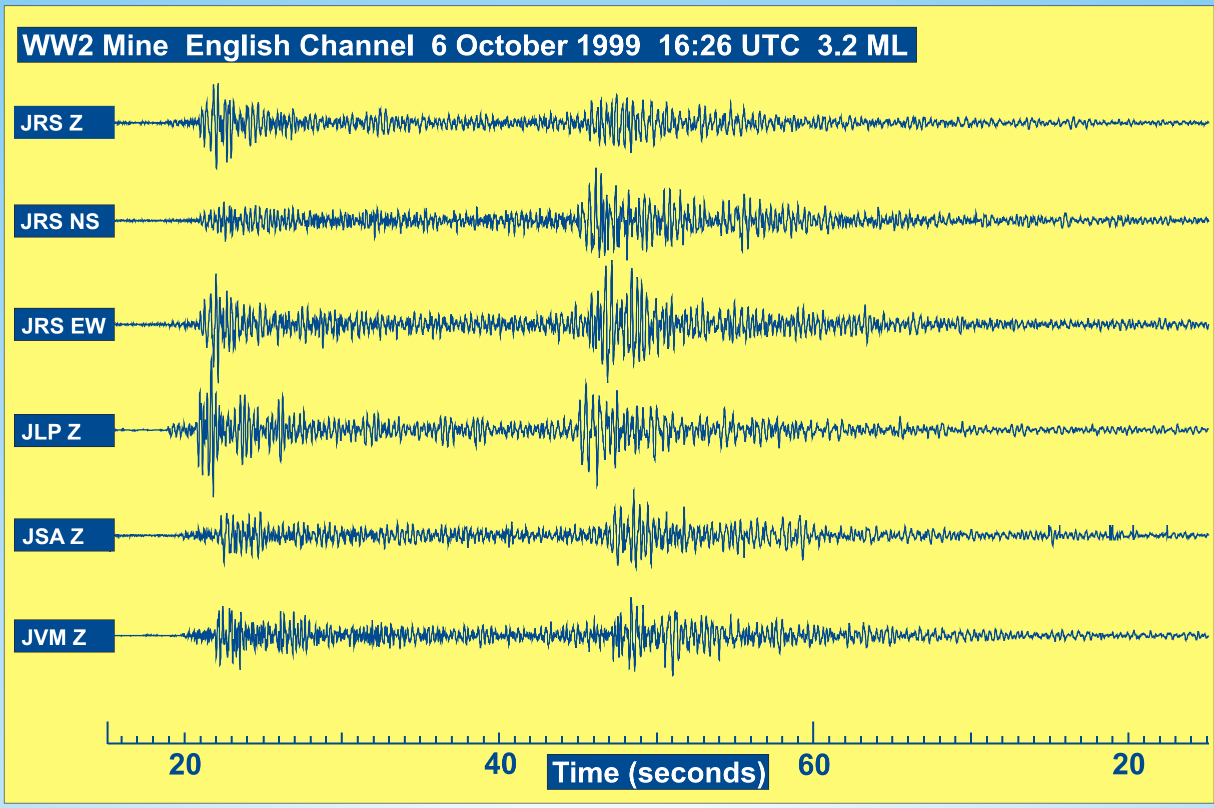


Figure 21. Seismograms recorded on the Jersey network from the magnitude 3.2 ML WW2 mine detonation in the English Channel on 6 October 1999 16:26 UTC. Three letter codes refer to stations in Annex E.

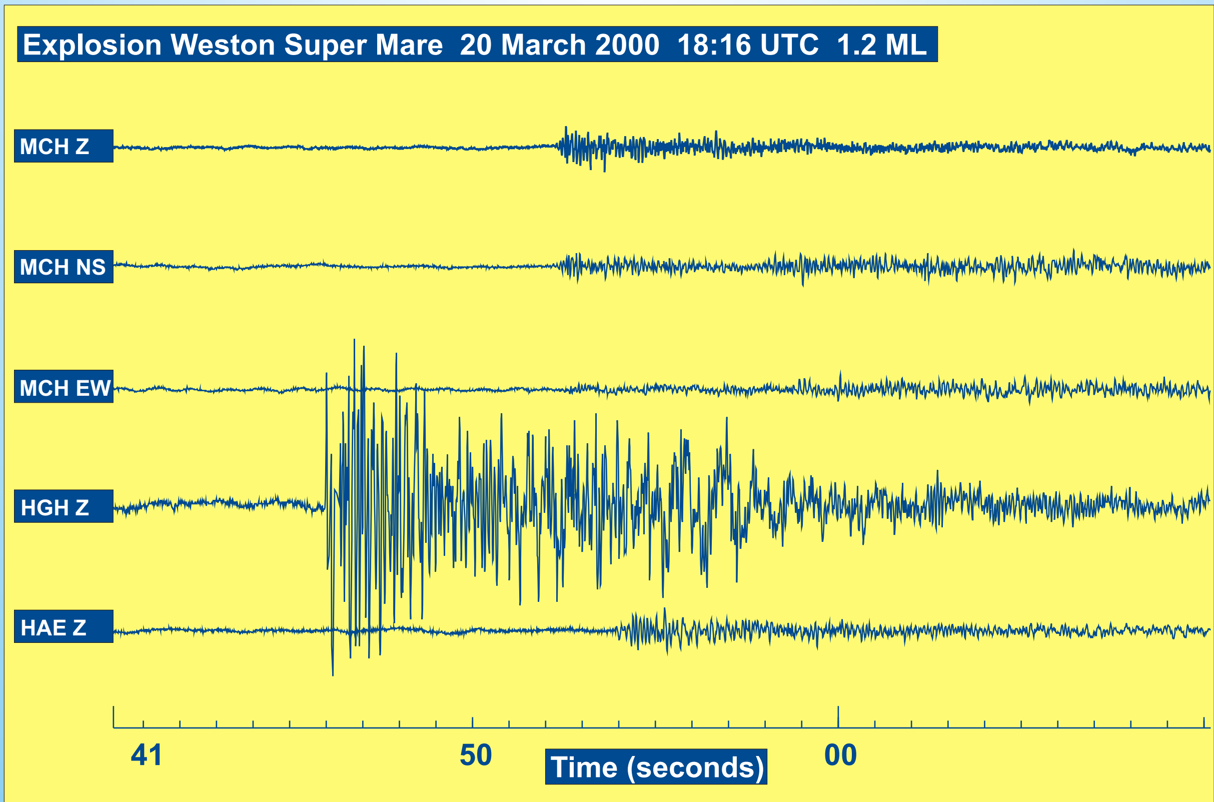


Figure 22. Seismograms recorded on the Hereford network from the magnitude 1.2 ML explosion in Weston Super Mare on 20 March 2000 18:16 UTC. Three letter codes refer to stations in Annex E.

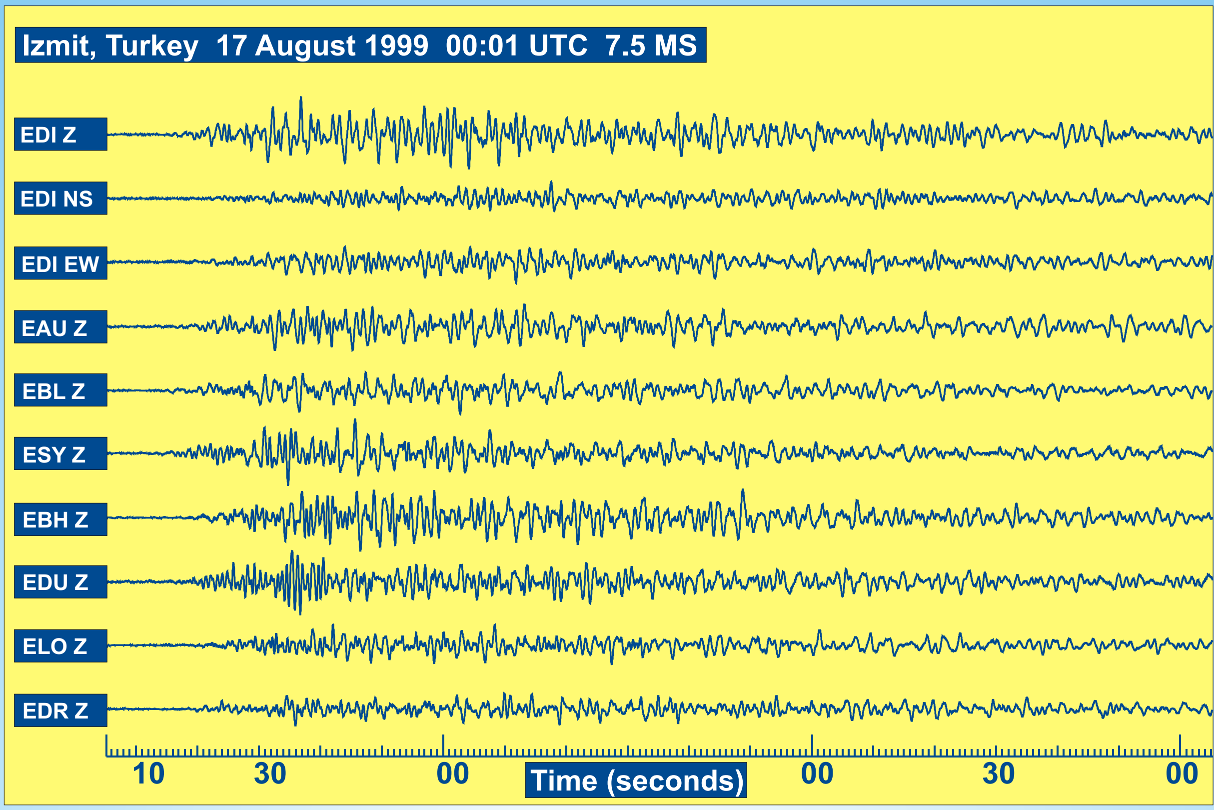


Figure 23. Seismograms recorded on the LOWNET network around Edinburgh from the magnitude 7.5 MS earthquake in Izmit, Turkey on 17 August 1999 00:01 UTC. Three letter codes refer to stations in Annex E.

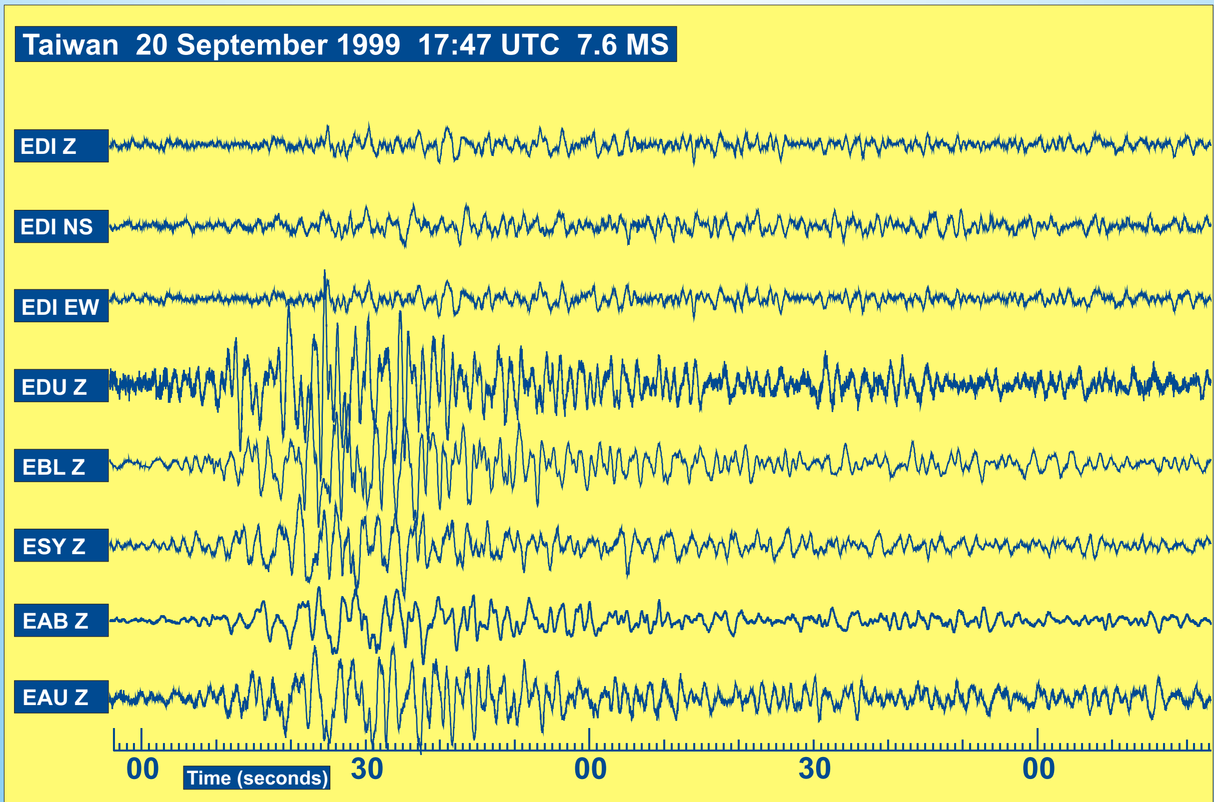


Figure 24. Seismograms recorded on the LOWNET network around Edinburgh from the magnitude 7.6 MS earthquake in Taiwan on 20 September 1999 17:47 UTC. Three letter codes refer to stations in Annex E.

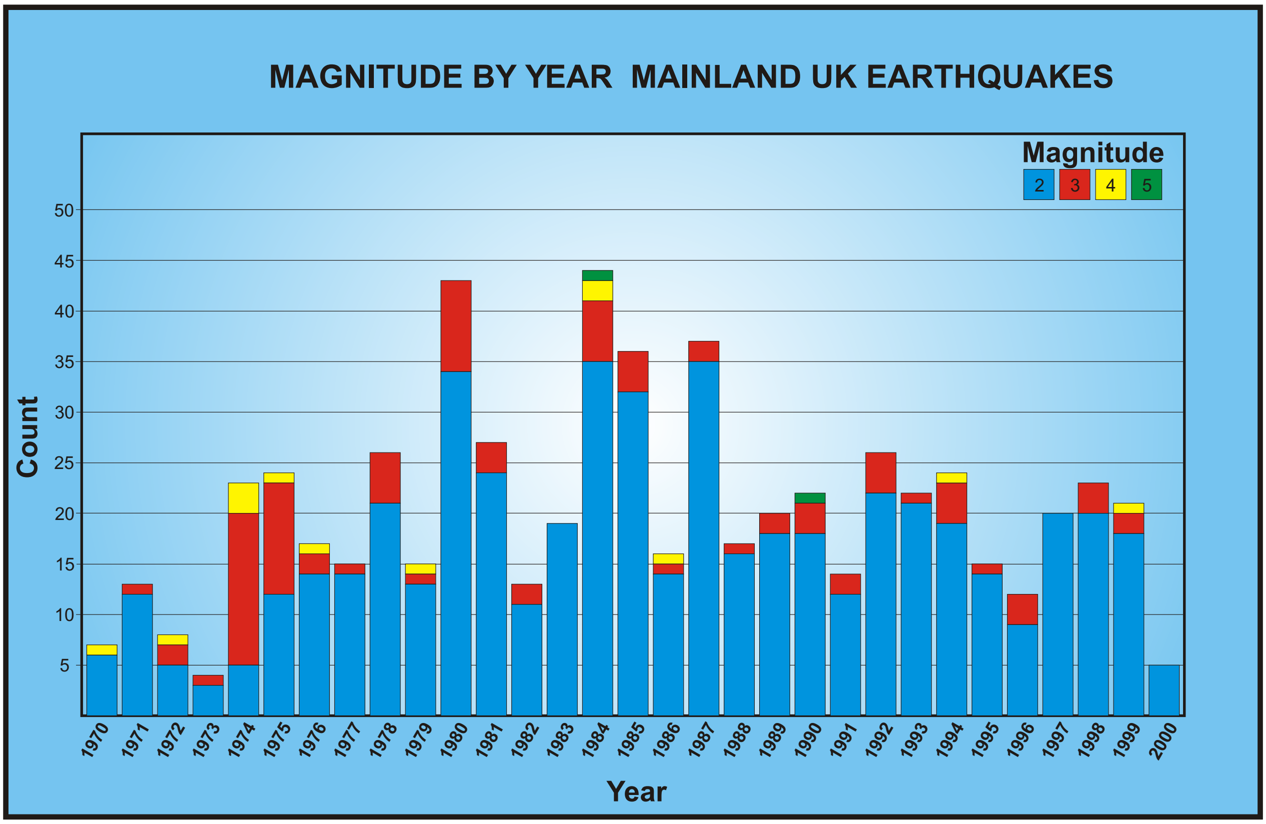


Plate 1. Histogram showing number of events magnitude 2.0 ML or above detected, 1970 - April 2000.

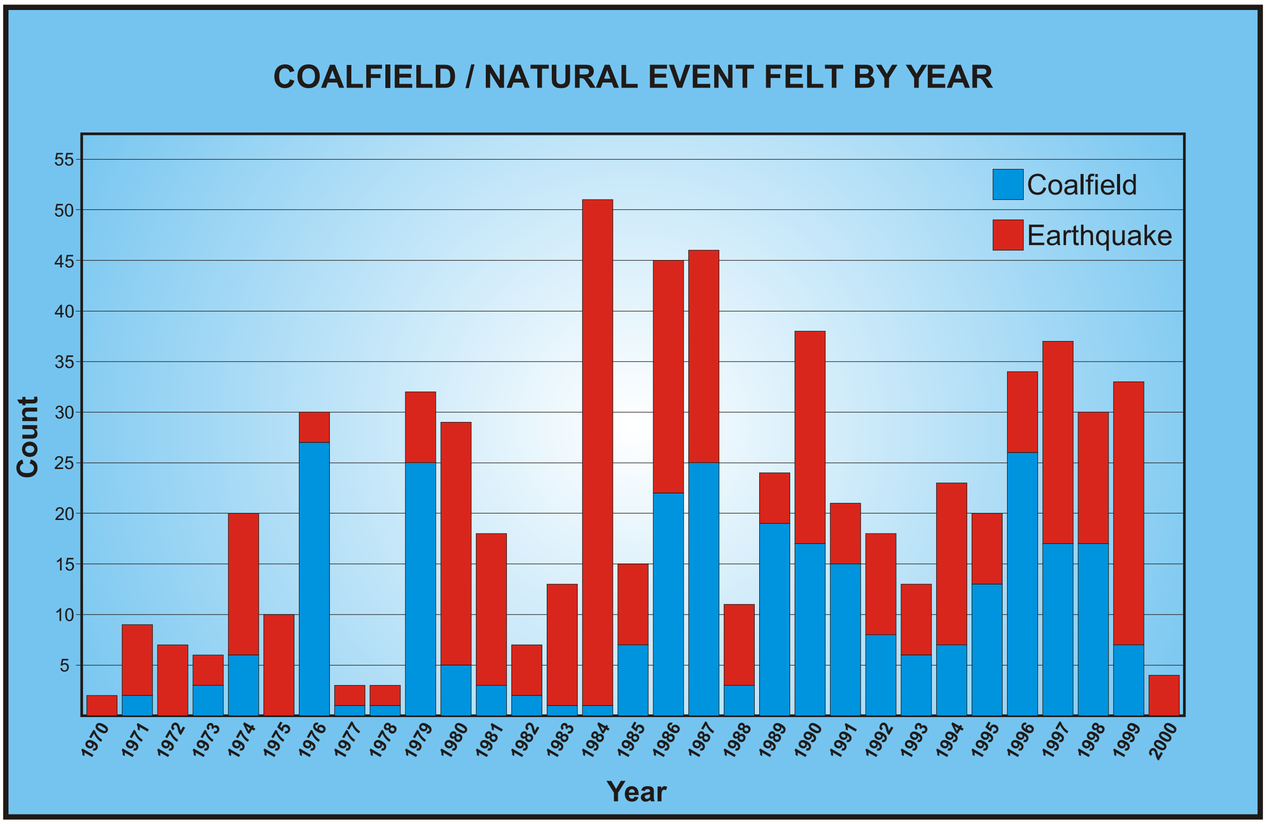


Plate 2. Histogram showing number of felt events 1970 - April 2000.

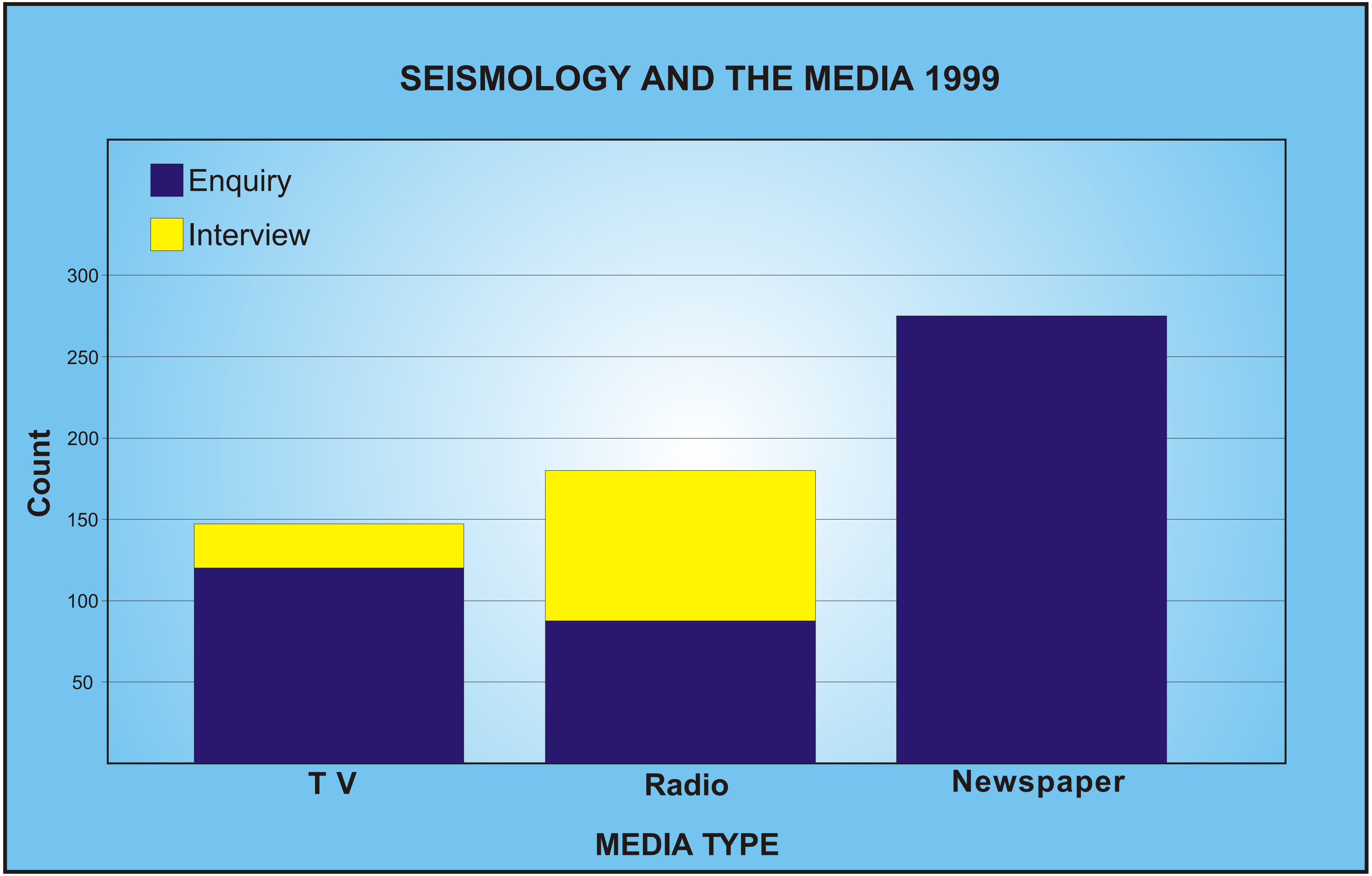


Plate 3. Histogram showing number of media enquiries answered for significant UK and world earthquakes in 1999.

Sennybridge Earthquake 25 October 1999 3.6 ML

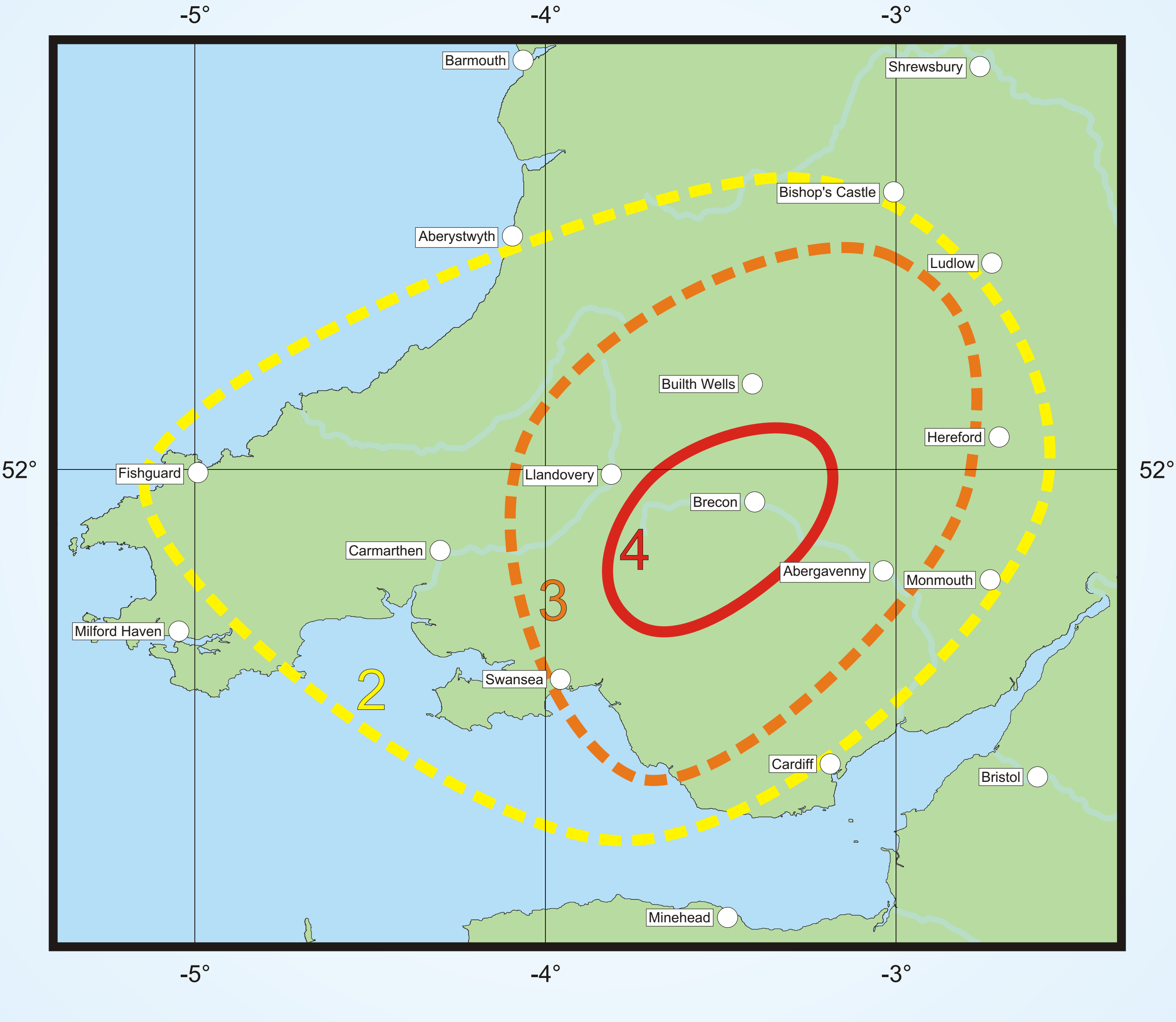


Plate 4. Sennybridge earthquake 25 October 1999 19:15 UTC, magnitude 3.6 ML - EMS Intensities.

Plate 5. Earthquake damage in the Gölcük region from the Turkey earthquake 17 August 1999 00:01 UTC, magnitude 7.5 Ms. (Photograph supplied by Dr Russ Evans, British Geological Survey).

Plate 6. Earthquake damage in the Düzce region from the Turkey earthquake 12 November 1999 16:57 UTC, magnitude 7.5 Ms. (Photograph supplied by Dr Paul Greening, University of Bristol).

Plate 7. Earthquake damage in the Athamis, Athens region from the Athens earthquake 7 September 1999 11:56 UTC, magnitude 5.8 Ms. (Photograph supplied by Professor. Amr S. Elnashai, EFTU/Imperial College, London)

Plate 8. Earthquake damage to the Shihkhang Dam, Tai-Chung from the Taiwan earthquake 20 September 1999 17:47 UTC, magnitude 7.6 Ms. (Photograph supplied by Dr Colin Taylor, University of Bristol).

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 Eleven)

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:1999

YearMoDy	HrMnSecs	Lat	Lon	kmE	kmN	Dep	Mag	Locality	Int	No	DM	Gap	RMS	ERH	ERZ	SQD	Comments
19990121	111018.2	53.09	0.07	538.7	357.1	16.9	2.8	BOSTON,LINCOLNSHIRE		9	46	141	0.11	1.1	1.9	B*C	15KM NE OF BOSTON
19990304	001651.8	55.40	-5.24	194.8	616.2	19.0	4.0	ARRAN,STRATHCLYDE	5	10	23	136	0.06	0.4	1.2	A*C	4KM SOUTH OF ARRAN
19990309	003843.2	56.87	6.36	909.2	806.2	15.0	3.0	NORWEGIAN-DANISH BASIN		12	530	333	0.37			D*D	
19990329	151547.3	53.65	-2.21	386.1	416.8	1.3	2.2	ROCHDALE,GTR MANCHESTER		12	26	68	0.24	1.1	2.0	B*C	C/F
19990405	031332.3	59.33	1.55	602.1	1054.1	18.8	2.9	NORTHERN NORTH SEA		19	178	150	0.14	0.8	1.8	A*D	
19990415	083104.0	57.02	-5.42	192.3	797.5	6.1	2.9	NEAR MALLAIG,HIGHLAND	3+	8	21	116	0.08	0.3	0.7	A*C	FELT GLEN GARRY...
19990511	072101.9	53.13	-1.09	460.8	359.8	2.9	2.1	MANSFIELD,NOTTS		7	28	184	0.12	1.1	2.2	B*D	C/F,6KM E OF MANSFIELD
19990515	071603.5	59.82	2.08	628.7	1110.6	15.0	2.2	NORTHERN NORTH SEA		8	183	172	0.35	7.7	7.2	D*D	
19990529	003141.7	62.28	4.58	741.2	1395.3	7.1	4.1	NORWEGIAN COAST	3+	14	80	285	0.38	5.3	3.0	D*D	FELT NORWEGIAN COAST
19990529	114934.5	57.25	-3.85	288.4	819.0	5.6	2.2	AVIEMORE,HIGHLAND	3+	10	38	101	0.16	1.1	5.8	C*C	FELT BOAT OF GARTEN
19990617	022026.6	51.99	-2.57	360.9	233.0	21.1	2.8	HEREFORD,HER & WORCS	3+	7	5	109	0.04	0.7	1.0	A*B	FELT CRADLEY
19990719	175814.0	56.38	-4.18	265.6	722.5	2.9	2.0	LOCH EARN,CENTRAL	3+	9	23	114	0.06	0.4	1.0	A*C	FELT ST FILLANS
19990730	093112.3	51.69	-3.20	317.0	199.7	6.4	2.7	BARGOED,MID GLAMORGAN		12	28	70	0.10	0.6	1.2	A*C	
19990731	075109.4	61.47	2.56	642.7	1295.5	10.1	2.2	NORTHERN NORTH SEA		14	127	201	0.39	5.2	5.5	D*D	
19990813	052858.6	51.69	-3.21	316.0	199.6	7.4	2.1	BARGOED,MID GLAMORGAN		8	37	91	0.13	1.0	5.8	C*C	
19990901	050054.6	53.20	-4.35	243.1	369.3	16.3	3.1	CAERNARVON,GWYNEDD	4	10	11	87	0.07	0.5	1.1	A*A	FELT CAERNARVON...
19990903	225750.5	55.23	-3.39	311.4	593.4	4.2	2.1	JOHNSTONEBRIDGE,D & G	3+	13	16	159	0.13	0.6		C*C	FELT JOHNSTONEBRIDGE...
19990907	120156.7	52.93	-2.27	381.6	337.2	3.1	2.6	NEWCASTLE-U-LYME,STAFFS	3+	8	31	147	0.11	0.9	1.9	A*C	FELT KEELE
19990908	054134.7	55.74	-6.41	123.1	658.6	9.1	2.0	ISLAY,STRATHCLYDE		11	68	209	0.20	2.0	2.5	B*D	
19990929	121125.2	60.73	-13.20	-208.9	1257.7	29.9	3.0	LOUSY BANK,N ATLANTIC		14	370	190	0.30	2.1	4.8	B*D	370KM WSW OF FAROES
19991002	035046.3	52.93	-2.28	381.2	337.4	3.9	2.4	NEWCASTLE-U-LYME,STAFFS	3+	8	31	147	0.11	1.0	2.1	B*C	FELT KEELE...
19991012	071727.3	49.52	-7.18	24.9	-29.3	15.0	2.7	SW OF SCILLY ISLES		8	135	351	0.08	8.9	3.0	D*D	70KM SW OF SCILLY ISLES
19991025	191520.7	51.97	-3.57	292.2	230.8	14.1	3.6	SENNYBRIDGE,POWYS	5	8	24	115	0.08	0.6	1.0	A*B	FELT BRECON...
19991122	010225.7	55.92	-5.89	157.0	676.4	7.9	2.7	JURA,STRATHCLYDE	2+	9	72	259	0.08	2.0		C*D	FELT ORMSARY
19991203	192843.3	55.87	-5.92	154.5	670.6	10.7	2.2	JURA,STRATHCLYDE		7	62	203	0.07	1.6	4.5	B*D	
19991205	194052.3	53.70	-2.13	391.5	422.7	7.6	2.3	BURNLEY,LANCASHIRE		6	25	209	0.08	1.7		C*D	9KM SW OF BURNLEY
19991214	094357.5	53.40	-2.42	372.2	389.1	8.0	2.8	ALTRINCHAM,G MANCHESTER		15	41	66	0.12	0.5		C*C	

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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 J BUCKLEY	- 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	NSV	- VULCAN
R WATSON	- HISCOX	DIRECTOR	- BGS, KEYWORTH
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

FROM: B Simpson
DATE: 25 October 1999
TIME: 23:40 BST
PAGES TO FOLLOW: 2

SEISMIC ALERT: SENNYBRIDGE, POWYS 25 OCTOBER 1999 19:15 UTC 3.5ML

BGS have received calls from the Police, the Dyfed County Emergency Planning Officer and numerous residents in Brecon, Llandrindod Wells, St Harmon and Rhayader who felt an earthquake at 19:15 UTC tonight. Felt reports described "the whole house shook", "everybody came running into the street", "the sofa moved" and "felt like an explosion".

The following preliminary information is available for this earthquake:

DATE	:	25 October 1999
ORIGIN TIME	:	19:15 20.7sUTC
LAT/LONG	:	51.97º North / 3.57º West
GRID REF	:	292.2 kmE / 230.9 kmN
DEPTH	:	14.6 km
MAGNITUDE	:	3.5 ML
INTENSITY	:	5+
LOCALITY	:	Sennybridge, Powys

Tonight's earthquake locates in the same general area as the magnitude 3.0 ML Llandrindod Wells earthquake on 20 September 1996, which was felt with intensities of 4 EMS in the epicentral area.

A seismogram of the earthquake, as recorded on the BGS Keyworth network and a map of instrumental seismicity within 50 km of the epicentre, 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	H PAYNE	- 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 J BUCKLEY	- 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	NSV	- VULCAN
R WATSON	- HISCOX	DIRECTOR	- BGS, KEYWORTH
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

FROM: Bennett Simpson
DATE: 20 January 2000
TIME: 11:15 UTC
PAGES TO FOLLOW: 1

SEISMIC ALERT: GRAMPIAN SONIC EVENT 20 JANUARY 2000 10:35 UTC

BGS have received felt reports via Grampian Police, local media and residents throughout the Grampian region of a felt event at approximately 10:36 UTC today. Felt reports described "the windows rattled", "the door rattled" and "heard a bang". Data from the BGS rapid-access network in the area were examined and a signal consistent with a sonic origin was recorded at 10:35 UTC.

RAF Flying Complaints and other militaryorganisations were contacted but could not confirm if any aircraft were operational at the time.

A seismogram of the event, as recorded on the BGS Moray network, is attached.

BGS STAFF WITH INPUT TO THE PROJECT

Dr Brian Baptie
Ms Jacqueline Bott
Dr Chris W A Browitt
Mr Daniel Dawes
Mr Peter S Day
Ms Janet Ferguson
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
Ms Maureen E A Ritchie
Mr David Scott
Mr Bennett A Simpson
Mr Dave A Stewart
Mr William A Velzian
Ms Alice B Walker

GEOGRAPHICAL CO-ORDINATES OF SEISMOGRAPH STATIONS USED BY BGS :MARCH 2000

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 2000

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 2000

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 2000

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.

BGS Seismology reports

WL/99/03 Walker, A.B. UK Earthquake monitoring 1998/99, BGS Seismic Monitoring and Information Service, Tenth Annual Report. June 1999.

WL/99/21 Henni, P.H.O., Lovell, J.H. & Lawrie, K.I.G, (2000). UK Historical Seismograms and Bulletins held in the NSA. February 2000.

WL/99/28 Riddick, J.C., Burgess, B.R., & Gibson, G. Verification of the Eskdalemuir Seismological Array GPS Survey. April 1999.

WL/99/31 Henni, P.H.O., and Lovell, J.H., (2000). Aberdeen University Seismological Material held in the NSA. February 2000.

WL/00/01 Walker, A.B. (ed), Ford, G.D., Galloway, D.D. and Simpson, B.A. Bulletin of British Earthquakes, 1999. March 2000.

WL/00/04 Musson, R.M.W., Mikkelsen, T. and Ziska, H., 2000. Historical seismicity of the Faroe Islands, January 2000.

In addition, 10 confidential reports were prepared for commercial customers and bulletins of seismic activity were produced monthly, up to 6 weeks in arrears, for the Customer Group sponsoring the project.

External Publications

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UK EARTHQUAKE MONITORING 1998/99 BGS SEISMIC MONITORING AND INFORMATION SERVICE: TENTH 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. Following a history of seismic monitoring over the past 30 years, 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 a major financial input from the Natural Environment Research Council (NERC). This Customer Group is listed in Annex A.

In the tenth year of the project (April 1998 to March 1999), one additional strong-motion instrument and four large capacity data storage disks were installed. Four strong-motion records were captured during the year from two of the seventeen sites now equipped with these instruments. Some gaps still remain in station coverage; notably in Northern Ireland. Other areas covered by site-specific networks in Jersey, northern Scotland, Outer Hebrides and the Orkney Islands, are vulnerable to closure owing to their dependency on funds from the commissioning bodies.

Some 201 earthquakes were located by the monitoring network in 1998, with 31 of them having magnitudes of 2.0 ML or greater and 30 reported to be felt by people. The largest felt earthquake in the reporting year (April 1998 to March 1999), with a magnitude of 4.0 ML, occurred 4 km south of Arran, Strathclyde on 4 March 1999. It was felt over an area of 18,500 km² (Isoseismal 3) and the maximum intensity in the epicentral region was 5 EMS (European Macroseismic Scale, Annex H). The largest offshore event occurred near Great Yarmouth on 16 May 1998, with a magnitude of 3.8 ML. In addition to earthquakes, BGS frequently receives reports of seismic events, felt and heard, which on investigation prove to be sonic booms, in coalfield areas, where much of the activity is probably induced by mining (eg Newcastle-Under-Lyme) or spurious. During the reporting period, data on nine controlled explosions and eleven 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. Monthly seismic bulletins were issued 6 weeks in arrears and, following revision, were compiled into an annual bulletin. 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 explored further using additional sensors. These now include radioactivity, ozone, sulphur dioxide, radon and NOx gases. Collaboration in this field is being explored with the Scottish and English Environment Agencies, Institute of Terrestrial Ecology (ITE), the water industry and the Meteorological Office. The aims of the 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. Following a history of seismic monitoring over the past 29 years, 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 a major financial input from the Natural Environment Research Council (NERC). This Customer Group is listed in Annex A.

UK HISTORICAL SEISMOGRAMS AND BULLETINS HELD IN THE NSA.

P H O Henni, J H Lovell, and K I G Lawrie

The National Seismological Archive (NSA) is the United Kingdom national repository for seismologically related material. It contains a wide range of original seismograms, bulletins, reports, and reference material from all over the world dating from the late 1800s onwards, and held in a variety of media.

Cataloguing of its holdings of over 100,000 UK historical seismograms and several hundred bulletins has been completed as part of an initiative to complete a full NSA database. This report presents the information in a format allowing researchers to ascertain what complementary material exists.

The collection has been catalogued, and incorporated into the electronically searchable NSA database. An online version of the report (.pdf) has been placed on the GSGG web pages at world-wide web address: http://www.gsrg.nmh.ac.uk/hazard/nsahome.htm

VERIFICATION OF THE ESKDALEMUIR SEISMOLOGICAL ARRAY GPS SURVEY

J C Riddick, B R Burgess and G Gibson

This report describes a Differential Global Positioning System survey carried out on the Seismological Array at Eskdalemuir. This work was carried out confirm the results obtained on an earlier survey, and also to provide additional information on previously un-surveyed locations. The results are presented with positions referenced to both OSGB36 and WGS84 datums.

ABERDEEN UNIVERSITY SEISMOLOGICAL MATERIAL HELD IN THE NSA.

P H O Henni and J H Lovell

A collection of seismological material held at Aberdeen University has been acquired by the National Seismological Archive as part of its initiative on the study of the history of seismology. This collection consists chiefly of seismograms, journals, and bulletins associated with the work at the Aberdeen University Observatory, but also contains some details of Dr Crombie's Observatory at Dyce, near Aberdeen, that was its immediate precursor.

The collection has been catalogued, and incorporated into the electronically searchable NSA database, together with Aberdeen material from other sources. An online version of the report (.pdf) has been placed on the GSGG web pages.

BULLETIN OF BRITISH EARTHQUAKES 1999

A B Walker (editor)

There have been 147 earthquakes located by the monitoring network during the year, with 27 of them having magnitudes of 2.0 ML or greater. Of these, 12 are known to have been felt, together with a further 21 smaller ones, bringing the total to 33 felt earthquakes in 1999.

The largest onshore earthquake, with a magnitude of 4.0 ML, occurred 4 km south of Arran on 4 March. A small aftershock 14 minutes later was also recorded, with a magnitude of 1.6 ML. The mainshock was felt up to 150 km away and over an area of 18,500 km^2. A macroseismic survey yielded over 1000 replies and the resulting map of felt effects is shown in Appendix A1. The highest observed intensity was 5 EMS at Lamlash, Arran, where in a number of cases, objects such as ornaments, pictures or toys fell or were displaced, and in a few cases heavy objects were also said to have been displaced, including two washing machines, a cooker, a microwave and a sofa. Although the area has been seismically active with small magnitude earthquakes, this magnitude 4.0 event is the largest in both the instrumental and historical catalogues. The nearest 3-component strong motion instrument to record the earthquake was 135 km distant and accelerations of 1.4, 4.0 and 3.6 mms^{-2}, were recorded for the vertical, NS and EW components, respectively. The focal mechanism produced for the Arran earthquake represents dominantly strike-slip faulting with a varying component of dip-slip motion. The nodal planes strike NW and NE and the P-axes are consistent with the regional stress direction for the UK.

The largest offshore earthquake occurred on the Norwegian coast on 29 May. It had a magnitude of 4.1 ML and was located approximately 360 km northwest of the Shetland Islands. It was felt on the Norwegian coast over an area of approximately 300 km^2. A further 5 events occurred in the North Sea and surrounding waters during the year, with magnitudes between 1.3 and 3.0 ML, and were located using both the BGS and Norwegian networks.

Near Boston, Lincolnshire, an earthquake, with a magnitude of 2.8 ML occurred on 21 January. Earthquakes of this size are usually felt when they occur onshore but enquiries to local police stations, post offices and coastguards, revealed that no felt reports were received. The time of day (11:10 UTC) and the depth of the earthquake (16.9 km) probably contributed to the lack of felt effects at the surface.

On 15 April an earthquake, with a magnitude of 2.9 ML, occurred near Mallaig, Highland. It was felt in Arnisdale, Loch Hourn and Glen Garry, with intensities of at least 3 EMS in the epicentral area. Felt reports described “a dull progressive rumbling” and “felt a shaking”. This is the largest event to have affected the area since the 30 January 1986 earthquake (magnitude 3.0 ML) which was also felt with intensities of at least 3 EMS.

Near Aviemore, Highland, an earthquake, with a magnitude of 2.2 ML, occurred on 29 May. Felt reports were received from residents of Boat of Garten, where intensities reached at least 3 EMS in the epicentral area. Felt reports described “the house shook” and “heard a loud bang”. This event locates in the same area as the magnitude 2.7 ML Aviemore earthquake which occurred in 1995 and was felt throughout the region with maximum intensities of 4 EMS.

An earthquake occurred near Hereford on 17 June, with a magnitude of 2.8 ML. Felt reports were received from residents of Cradley and Welland, where intensities reached at least 3 EMS in the epicentral area. A single report was received from a resident in Cradley (who was awake at the time), some 18 km northeast of the epicentre, who described “the whole cottage shook like a heavy lorry passing outside” and “the dressing table rattled”. This event was recorded on the strong motion instrument near Hereford, some 33 km away, where accelerations of 8, 20 and 12 mms^{-2} for the vertical, NS and EW components, respectively, were measured. A focal mechanism for the event was calculated using data from stations up to 169 km away and shows dominant normal faulting with a component of strike-slip motion. The area has been seismically active in the past with earthquakes of 5.2 and 5.3 occurring in 1863 and 1896, respectively. These events were felt over most of England and Wales and caused damage in the epicentral area (Musson, 1994).

An earthquake, with a magnitude of 1.8 ML, occurred 6 km west of Jersey, Channel Islands on 13 July. Thirty five felt reports were received via colleagues at Jersey Airport, who had been contacted by residents throughout the west side of Jersey. Felt reports described “heard a loud noise”, “the walls and roof rattled”, “the house shook” and “the window and cooker shook”. The event locates approximately 5 km north west of the felt earthquake on 22 June 1997, which had a magnitude of 2.2 ML.

Near Loch Earn, an earthquake, with a magnitude of 2.0 ML, occurred on 19 July. Felt reports were received from residents of the village of St Fillans, where intensities reached at least 3 EMS. Felt reports described “the building shook violently” and “felt like a car crashing into the side of the house”. This is the first earthquake to be reported felt in the area and is the largest to be located since the 26 November 1975 Glen Almond earthquake which had a magnitude of 2.4 ML.

A magnitude 3.1 ML earthquake occurred near Caernarvon, Gwynedd on 1 September. It was felt as far away as Barmouth, 60 km to the south and in Rhyl, 55 km to the east. Felt reports described “the whole house vibrated” and “heard loud rumblings and vibrations”. This earthquake was followed by a magnitude 1.2 ML aftershock, which was reported felt in the Llangefni area. A macroseismic survey was conducted for the main event and over 100 replies were received, giving a maximum intensity of 4 EMS. The event locates some 7 km northeast of the Caernarvon Bay earthquake which occurred on 29 July 1992, and was felt over 10,000 km^2 and had a magnitude of 3.5 ML.

Two felt earthquakes with magnitudes of 2.1 and 1.3 ML, occurred in the Johnstonebridge area of Dumfries and Galloway, with intensities of 3 and 2 EMS, respectively, on 3 September. Felt reports described “like an explosion” and “heard a loud rumble”. The area around Johnstonebridge has been seismically active for a number of years with most of the swarm activity occurring to the west of these events.

On 29 September, an earthquake with a magnitude of 3.0 ML, was located 370 km WSW of the Faroe Islands, in the North Atlantic. It was located using data from the recently installed station in the Faroe Islands (FTO), two Icelandic stations and the UK network.

An earthquake with a magnitude of 3.6 ML, occurred near Sennybridge, Powys on 25 October. Felt reports described “everybody came running out into the street”, “the whole house shook” and “felt like an explosion”. A macroseismic survey was conducted and around 200 replies were received, giving a maximum intensity of 5 EMS. The focal mechanism for the Sennybridge earthquake represents dominant normal faulting with a varying component of strike-slip motion. The trend of the P-axis is consistent with that of the NW trending regional direction; however, the plunge of the P-axis varies from vertical to horizontal with increasing degrees of the strike-slip component of movement. Two weeks after the event, a small aftershock, with a magnitude of 1.9 ML was located in the same area. In the past thirty years, the area has experienced a number of small earthquakes (up to 2.6 ML) but historically, it has been affected by large earthquakes with magnitudes over 5.0 ML. They occurred near Swansea some 40 km to the southwest in 1727, 1775 and 1906 and caused damage in the epicentral area and were felt up to 200 km away.

On 22 November, an earthquake with a magnitude of 2.7 ML, occurred on Jura, Strathclyde. Felt reports described "sounded like a long rumble" and "the house shook". This earthquake locates approximately 20 km southeast of the magnitude 3.5 ML Jura earthquake on 3 May 1998, which was felt with intensities of 4 EMS in the epicentral area. Two further Jura events occurred on 3 December in the same area, with magnitudes of 2.2 and 1.8 ML; no felt reports were received for either of these events. Offshore Jura, two events with magnitudes of 1.7 and 1.5 ML occurred on 4 and 15 September, respectively. No felt reports were received.

Near Altrincham, Greater Manchester, an earthquake, with a magnitude of 2.8 ML occurred on 14 December. Earthquakes of this size are usually felt when they occur onshore but enquiries to Manchester Police, revealed that no felt reports were received. The time of day (09:43 UTC) and the location, which is close to a motorway and Manchester Airport, probably contributed to the lack of felt effects at the surface.

Three earthquakes were detected in the Blackford area of Tayside during 1999, with magnitudes of 0.7, 0.8 and 0.7 ML. 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. In the same general area, in 1979, the magnitude 3.2 ML Ochil Hills earthquake was felt with a maximum intensity of 5 EMS.

Nine events, with magnitudes ranging between 0.6 and 1.9 ML, occurred near Dumfries, Dumfries and Galloway. Seven of these events were felt by local residents in the Newfield, Troston, Kirkton and Tinwald areas of Dumfries and Galloway.

In North Wales, three events with magnitudes of 1.2, 0.1 and –0.2 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 coalfield areas of central Scotland, Yorkshire, Staffordshire, West Midlands, Mid Glamorgan and Nottinghamshire continued to experience shallow earthquake activity which is believed to be mining induced. Some 25 coalfield events, with magnitudes ranging between 0.5 and 2.2 ML, were detected during the year. Seven of these were reported felt by local residents.

Two shallow events occurred near Newcastle-under-Lyme, Staffordshire, with magnitudes of 2.4 and 2.6 ML, both of these events were felt by local residents in the Keele and Newcastle-under-Lyme areas of Staffordshire, with intensities of at least 3 EMS.

Five events, with magnitudes ranging between 0.5 and 1.4 ML, were located near Clackmannan in the central region of Scotland. Three of these events were felt by local residents in the Forest Mill area. This is an area which has experienced many such mining induced events in the past.

The seismograph network detected two events near Donegal, Ireland with magnitudes of 1.7 and 1.3 ML. BGS received felt reports for both events via colleagues in Ireland and locations were achieved using both the BGS and DIAS (Ireland) seismograph networks.

INSTRUMENTAL SEISMICITY OF WESTERN AND CENTRAL SCOTLAND, 1969-1999

J D Bott, A B Walker and M E A Ritchie

Continuous seismic monitoring began in the UK in the late 1960s with the installation of a small network around Edinburgh and one station at Kyle in NW Scotland. Seismographic coverage improved in Scotland in the 1980s with the addition of over 20 stations which allowed for the location of earthquakes as small as ML 1.5. The installation of more stations in the far north of Scotland in 1995 has significantly improved the location capabilities across the region.

Western and central Scotland is one of the most seismically active regions of the UK, where about 40% of all instrumental earthquakes have been located. Historically, the largest earthquake occurred in Argyll, west central Scotland, in 1880 with a macroseismic ML of 5.2 and was felt throughout most of Scotland and northern Ireland. In the last 30 years there have been five earthquakes of ML 4.0 and greater, the largest occurred within the 1974 Kintail swarm with ML 4.4. The majority of instrumental (and historical) earthquakes locate within a wedge-shaped region in western and central Scotland, with few earthquakes occurring in the NE and far north of Scotland. The apex of the wedge is situated on the west coast of Scotland about 58degN, and its abrupt boundaries run SSE and SSW from this point. The southern boundary converges south of Kintyre and along its SE side it strikes parallel to the Highland Boundary fault. Most well located earthquakes within the region have shallow focal depths (less than 10 km) but some have occurred south of Arran at depths of up to 19 km. Focal mechanisms have been difficult to constrain in this region, but a mechanism was obtained for the recent ML 4.0 Arran earthquake which shows predominantly strike-slip faulting on either NW- or NE-striking planes. The dip of the latter plane is poorly constrained. This focal mechanism is consistent with the NW-SE maximum compressive stress direction observed for the UK.

METHODOLOGICAL CONSIDERATIONS OF PROBABILISTIC SEISMIC HAZARD MAPPING

R M W Musson

The study of seismic hazard is perhaps the most practically oriented aspect of earthquake seismology. As such, it should not be treated in an idealised or academic manner, but with regard to the needs of the consumers of the final product. This has important consequences when it comes to the topic of probabilistic seismic hazard maps. Who are these for? Historically, early studies of probabilistic seismic hazard tended to be done for engineers for specific design requirements. Consequently, there has been a tendency to treat seismic hazard maps as a sort of pan-national study for engineers, who can identify the design requirements for any site by picking them from the map. A dissenting point of view argues that seismic hazard maps are by their very nature too generalised to be used in this way; that such maps provide a first indication of relative hazard and should not be a substitute for site studies. There are, therefore, a number of interesting and important methodological questions to be asked: what are the practical differences in undertaking a seismic hazard map from calculating hazard for a site? Should probabilistic seismic hazard maps have the same degree of conservatism as site studies? How can seismologists meet the needs of different audiences? An engineer may think in terms of ground acceleration, but this parameter probably means little to people in other professions who still need access to seismic hazard data, but in a form they can understand. These are questions that need to be addressed directly; one should not leave them to be answered by default.

COMPARISON OF SOME MACROSEISMIC EPICENTRE LOCATION METHODS

R M W Musson

The provision of spatial co-ordinates for historical earthquakes, derived from macroseismic data, can follow one of two objectives. The first is to try to determine, from macroseismic evidence, what point would have been cited as the epicentre in the sense that this term is used in modern instrumental catalogues. The second is to determine some conventional point representing the focus from which the strongest shaking appears to radiate. The term barycentre has been suggested for such a point. It can be argued that the latter approach is more appropriate for seismic hazard studies, in which the aim is to characterise the field of strong shaking of future earthquakes. On the other hand, such an approach, if it is to be pursued consistently, requires one to jettison all instrumental earthquake catalogues, which may not be practical. This paper compares some simple approaches to making automatic epicentre determinations from macroseismic data and examines their accuracy with respect to instrumentally determined epicentres.

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.

SUMMARY OF EARTHQUAKES IN 1999

D D Galloway and A B Walker

Overseas

This year was not exceptional in terms of the number of worldwide earthquakes (Figure 1). There were no 'great' earthquakes (magnitude over 8.0), 12 'major' earthquakes (magnitudes between 7.0 and 7.9) and 71 'strong' earthquakes (magnitudes between 6.0 and 6.9). These numbers are less than the long-term averages for these magnitude ranges, which are 1, 18 and 120, respectively. However, the year was significant in terms of the number of people killed by earthquakes, which was over 22,000 (Table 1). This is approximately three times greater than the long-term average of 8,700 and the highest annual death toll since 1990.

The largest and most disastrous earthquake during the year, with a magnitude of 7.4 Ms, occurred on 17 August in NW Turkey. It killed some 17,100 people (some 78% of the fatalities from earthquakes in 1999), injured over 44,000 and some 350,000 buildings were either damaged or destroyed. The epicentre of the earthquake was 11 km SE of the industrial city of Izmit, which has a population of over one million. Most of the damage and fatalities occurred in Izmit and Gölcük. The earthquake occurred on the northern part of the North Anatolian Fault system at a depth of about 17 km. The mechanism was right-lateral strike-slip and the movement produced 60 km of surface rupture and offsets up to 2.7 metres. A second fatal and damaging earthquake, with a magnitude of 7.5 Ms, occurred approximately 100 km east of the 17 August event, in November, near the city of Düzce. It killed over 840 people, injured almost 5,000 more and caused extensive damage in the Ankara-Istanbul-Kaynasli area. Several other significant events occurred in the northern Turkey area during the year causing the deaths of a further 11 people, injury to hundreds more and additional damage to Izmit and Düzce.

On 20 September, an earthquake with a magnitude of 7.5 Ms, occurred near the town of Chi-Chi in Nantou County, central Taiwan, approximately 150 km south of Taipei. It killed at least 2,400 people, injured some 10,000 more and caused damage to over 82,000 housing units leaving around 300,000 people homeless. The most affected areas were Nantou and Taichung counties. Two more earthquakes in the area on 25 September (magnitude 6.4 Ms) and 22 October (magnitude 5.6 Ms), caused further damage and additional casualties. The cost of the damage for the earthquakes in Taiwan is estimated at US$14 billion. Five earthquakes of similar destructive potential as this one have occurred on the west coast of Taiwan in the past 150 years; a magnitude 6.5 event in 1848 killing 1000, a magnitude 6.5 event in 1862 killing 1000, a magnitude 7.0 event in 1906 killing 1276 and a magnitude 7.1 event in 1935 killing over 3200, with a magnitude 6.5 aftershock which killed a further 2746.

The year started off with a destructive earthquake, on January 25, in the mountainous region bordering the five provinces of Quindio, Risaralda, Tomila, Valle del Cauca and Caldas in Colombia. It had a magnitude of 5.9 Mb and killed 1,186 people, injured 8,563, destroyed or damaged approximately 80,000 homes and left over 90,000 families homeless. Among the 28 towns affected, Armenia, the provincial capital of Quindio, was the worst hit, where 907 people were killed and approximately 70% of buildings were destroyed including hospitals and police and fire stations.

In Afghanistan, on 11 February, 70 people were killed during a magnitude 5.8 Ms earthquake in the region. Over 500 people were injured and about 150,000 were left homeless in the Wardak and Logar Provinces after the destruction or severe damage to over 18,000 homes. A smaller event minutes before served as a warning, and possibly contributed to the relatively low death toll since people had already fled outside. There were over 40 severe aftershocks reported, which drove earthquake victims to seek safety by sleeping outdoors, despite wet weather and freezing temperatures of up to minus 8°C.

On 21 February, in the Eastern Caucasus republic of Azerbaijan, an earthquake with a magnitude of 5.1 Mb killed one person, caused injury to 20 others and badly damaged several homes and buildings in the Kizilyurt area, of Russia. On 4 June, in the same general area, a magnitude 5.4 Mb earthquake caused injury to 15 people and damaged 150 houses in Agdash.

In SE Iran, on 4 March, an earthquake with a magnitude of 6.5 Ms, killed 1 person, when her house collapsed, and severely damaged 520 homes in the Kerman and Hormuzgan Provinces. The earthquake was felt strongly in the three Provinces of Kerman, Hormozgan and Fars, Iran, and was also felt in Dubai, United Arab Emirates, approximately 550 km SW of the epicentre.

On 28 March, in the Uttar Pradesh region of northern India, an earthquake with a magnitude of 6.6 Ms caused extensive damage in the districts of Chamoli, Rudraprayag, Bageshwar, Tehri Garhwal and Pauri Garwhal. The earthquake killed over 100 people, injured 390 and left over 21,100 houses destroyed. Many roads were blocked by landslides in the epicentral area including a 16 km stretch of road leading to Chamoli.

In Peru, on 3 April, one person was killed in the Camana area, another 50 were injured and over 300 houses were damaged in the Arequipa area, during a magnitude 6.2 Ms earthquake. Landslides were reported from the epicentral area where the Pan American highway was blocked in four different locations in southern Peru.

On 22 April, an earthquake, with a magnitude of 5.7 Mb, killed 2 people in a gold mine and damaged some buildings in the Welkom area in the Republic of South Africa.

In the SW Fars Province of southern Iran on 6 May, an earthquake, with a magnitude of 6.3 Ms, killed 26 people, injured more than 100 and destroyed over 800 homes. Three aftershocks, with magnitudes of 5.3, 4.5 and 4.4 Mb, within 30 minutes of the mainshock, contributed to the overall damage. Roads and power plants were destroyed and electricity, telephone and water services were widely disrupted in the epicentral area. The epicentres of these earthquakes are approximately 550 km NW of the magnitude 6.5 Ms SE Iran earthquake on 4 March earlier in the year.

Two fatal and damaging earthquakes occurred in Mexico during 1999. The first, on 15 June, with a magnitude of 6.5 Ms, killed 20 people, injured 200 others and destroyed or damaged thousands of buildings and several bridges in central Mexico. The state of Puebla was worst affected where several historic buildings were damaged. The epicentre of the earthquake is approximately 200 km SE of Mexico City. The second, on 30 September, with a magnitude of 7.5 Ms, killed 33 people and injured 160 others. It caused damage to more than 5,000 homes and 150 historical buildings in the state of Oaxaca, most of them churches and monasteries, and also damaged some 1,300 schools.

In Guatemala, one person was killed, another died from a heart attack, 40 people were injured and several houses, bridges and highways were damaged in the Izabel-Puerto Barrios area as a result of an earthquake on 11 July. The earthquake, with a magnitude of 6.6 Ms, was located on the Caribbean coast of Honduras and Guatemala about 275 km NE of Guatemala City. It was felt throughout most of Guatemala, Honduras, Belize, El Salvador and in parts of Mexico.

On 22 July, an earthquake with a magnitude of 5.2 Mb, occurred in the Bay of Bengal. It killed 6 people, injured over 200 and caused damage to over 700 homes on Maheshkhali Island and Cox's Bazaar, Bangladesh.

In northern Iran, on 10 August, an earthquake, with a relatively small magnitude of 4.5 Mb, killed one person, injured another and damaged several houses at Momenabad, Iran.

In Athens, Greece, on 7 September, a magnitude 5.8 Ms earthquake killed 143 people, injured thousands more and completely or partially damaged over 74,000 homes affecting over 200,000 people. The areas that suffered most destruction were the relatively poorer suburbs of Athens, some of which include Menidi, Ano Liosia, Thracomacedones, Philadelfia, Metamorphosi, Ilion and Galatsi. It was felt throughout most of central Greece, as far away as Corinth, 100 km to the south, and was also felt in parts of Turkey. Damage, as a result of this earthquake, has been estimated at US$655 million.

On 26 November, an earthquake, with a magnitude of 7.3 Ms, offshore the Vanuatu Islands, resulted in the deaths of 10 people. Five were killed at Ena Village in the north of Pentecost Island and another five were drowned at Baie Marteli, on the southern tip of Pentecost Island, by the locally generated tsunami which occurred 15 minutes after the earthquake. Hundreds more were injured and thousands more were made homeless mainly as a result of the tsunami. Extensive damage to houses, communal buildings, churches, schools, roads and concrete water tankers was reported from the mainly affected Islands of Pentecost, Ambrym and Paama.

On 11 December, an earthquake, with a magnitude of 7.1 Ms, killed 6 people and injured 40 others near Luzon in the Philippine Islands. Most of the casualties were caused by falling debris from damaged walls and roofs in their homes.

In the Sunda Strait area, on 21 December, 5 people were killed, 220 were injured and hundreds more were made homeless as 2,800 buildings and houses were damaged in western Java during a magnitude 6.1 Mb earthquake.

On 22 December, in northern Algeria, an earthquake with a magnitude of 5.5 Ms, caused extensive damage and disrupted power, telephone and water services throughout the Ain Temouchant area. At least 28 people were killed, 200 were injured and over 3,000 buildings were destroyed, affecting almost 5,000 families (approximately 25,000 people). This earthquake was felt throughout northern Algeria and as far away as Oujda, Morocco.

The UK summary of earthquakes is covered in the summary for the 1999 bulletin of British earthquakes above.

FROM QUESTIONNAIRES TO INTENSITIES - ASSESSING FREE-FORM MACROSEISMIC DATA IN THE UK

R M W Musson and P H O Henni

Questionnaires for macroseismic surveys can generally be categorised into two groups: structured questionnaires, where respondents are given a number of options and have to tick one, and free-form questionnaires, where open-ended questions are answered by the respondents in their own words. Both have advantages and disadvantages. The structured approach is easier for the seismologist to process and is more focussed on the answers he wants to receive. The free-form approach is better at preserving nuances and qualifications to the respondents' answers that might otherwise be lost. Free-form questionnaires can be a lot shorter than structured ones, and it is partly for this reason that practice in the UK since 1974 has been to employ such a questionnaire design; short questionnaires can be distributed widely by being printed in local newspapers. The questionnaires received are then sorted by place, and for each place a synopsis sheet is prepared summarising the reported effects. Intensities are then assigned from the synopsis sheets, with reference back to the questionnaires where necessary. Data are checked using a pseudo-GIS program, and the final maps are prepared with the GMT mapping package.

HOW TO MAP AN EARTHQUAKE

R M W Musson

The strength of an earthquake at any place is measured by its intensity, which requires no specialised equipment to measure since it is dependent on descriptions of actual observed effects. After an earthquake has happened, a seismologist will attempt to collect people's experiences and compare them to the intensity scale. Much of this information is collected using questionnaires, which can be used for doorstep interviews, or left for people to collect from libraries or post offices, or even published in a newspaper. If the earthquake has caused damage, then a trip has to be made to the area where the damage occurred to record how bad it was. Once all the intensity numbers have been found, they can be plotted on a map. Usually the seismologist will then want to draw some contours for the different intensity values. Such maps can be used to work out what sort of effects can be expected from earthquakes in the future, when one knows how rapidly the shaking decreases with distance. This sort of study makes an ideal school project.

CONSTRAINTS ON THE FREQUENCY-MAGNITUDE RELATION AND MAXIMUM MAGNITUDES IN THE UK FROM OBSERVED SEISMICITY AND GLACIO-ISOSTATIC RECOVERY RATES

I Main, D Irving, R M W Musson and A Reading

Earthquake populations have recently been shown to have many similarities with critical-point phenomena, with fractal scaling of source sizes (energy or seismic moment) corresponding to the observed Gutenberg-Richter (G-R) frequency-magnitude law holding at low magnitudes. At high magnitudes, the form of the distribution depends on the seismic moment release rate M and the maximum magnitude mmax. The G-R law requires a sharp truncation at an absolute maximum magnitude for finite M. In contrast, the gamma distribution has an exponential tail which allows a soft or 'credible' maximum to be determined by negligible contribution to the total seismic moment release. Here we apply both distributions to seismic hazard in the mainland UK and its immediate continental shelf, constrained by a mixture of instrumental, historical and neotectonic data. Tectonic moment release rates for the seismogenic part of the lithosphere are calculated from a flexural-plate model for glacio-isostatic recovery, constrained by vertical deformation rates from tide-gauge and geomorphological data. Earthquake focal mechanisms in the UK show near-vertical strike-slip faulting, with implied directions of maximum compressive stress approximately in the NNW-SSE direction, consistent with the tectonic model. Maximum magnitudes are found to be in the range 6.3-7.5 for the G-R law, or 7.0-8.2 m, for the gamma distribution, which compare with a maximum observed in the time period of interest of 6.1 ML. The upper bounds are conservative estimates, based on 100 per cent seismic release of the observed vertical neotectonic deformation. Glacio-isostatic recovery is predominantly an elastic rather than a seismic process, so the true value of mmax is likely to be nearer the lower end of the quoted range.

DETERMINATION OF DESIGN EARTHQUAKES IN SEISMIC HAZARD ANALYSIS THROUGH MONTE CARLO SIMULATION

R M W Musson

A method is demonstrated using Monte Carlo simulation (stochastic modelling) techniques that allows the extraction of information about design earthquakes that constitute the most likely combinations of earthquake magnitude/epicentral distance that would actually generate the computed hazard ground motion at a site of interest, taking into account the lognormal scatter in the attenuation relationship. A worked example, at three different return periods, is shown for a realistic case in Greece. The results demonstrate the range of events that may contribute to the hazard, from which median or modal values can be derived. This method should be very useful in cases where it is desired to select earthquake time series representing the hazard for engineering analyses. In the example shown the most probable magnitude/distance pairs are such that would produce predicted deterministic acceleration values of about half the design ground motion.

PROBABILISTIC SEISMIC HAZARD MAPS FOR THE NORTH BALKAN REGION

R M W Musson

A set of seismic hazard maps, expressed as horizontal peak ground acceleration, have been computed for a large area of Central and Eastern Europe covering the North Balkan area (Former Yugoslavia, Hungary, Romania). These are based on (a) a compound earthquake catalogue for the region; (b) a seismic source model of 50 zones compiled on the basis of tectonic divisions and seismicity, and (c) a probabilistic methodology using stochastic (Monte Carlo) modelling. It is found that the highest hazard in the region comes from intermediate focus earthquakes occurring in the Vrancea seismic zone; here the hazard exceeds 0.4 g at return periods of 475 years. Special account has been taken of the directional nature of attenuation from this source.

GENERALISED SEISMIC HAZARD MAPS FOR THE PANNONIAN BASIN USING PROBABILISTIC METHODS

R M W Musson

A set of seismic hazard maps, expressed as horizontal peak ground acceleration, are presented for a large area of Central and Eastern Europe covering the Pannonian Basin and surrounding area. These are based on (a) a compound earthquake catalogue for the region; (b) a seismic source model of 50 zones compiled on the basis of tectonic divisions and seismicity, and (c) a probabilistic methodology using stochastic (Monte Carlo) modelling. It is found that the highest hazard in the region comes from intermediate focus earthquakes occurring in the Vrancea seismic zone; here the hazard exceeds 0.4 g at return periods of 475 years. Special account has been taken of the directional nature of attenuation from this source. The maps are intended for use in studies of comparative methodologies for seismic hazard assessment.

THE USE OF MONTE CARLO SIMULATIONS FOR SEISMIC HAZARD ASSESSMENT IN THE UK

R M W Musson

The input required for a seismic hazard study using conventional probabilistic seismic hazard assessment (PSHA) methods can also be used for probabilistic analysis of hazard using Monte Carlo simulation methods. This technique is very flexible, and seems to be under-represented in the literature. It is very easy to modify the form of the seismicity model used, for example, to introduce non-Poissonian behaviour, without extensive reprogramming. Uncertainty in input parameters can also be modelled very flexibly - for example, by the use of a standard deviation rather than by the discrete branches of a logic tree. In addition (and this advantage is perhaps not as trivial as it may sound) the simplicity of the method means that its principles can be grasped by the layman, which is useful when results have to be explained to people outside the seismological/engineering communities, such as planners and politicians. In this paper, some examples of the Monte Carlo method in action are shown in the context of a low to moderate seismicity area: the United Kingdom.

MAIN RESULTS OF THE PROJECT “BEECD”: A BASIC EUROPEAN EARTHQUAKE CATALOGUE AND A DATABASE FOR THE EVALUATION OF LONG-TERM SEISMICITY AND SEISMIC HAZARD

M Stucchi, P Albini, R Camassi, R M W Musson and R Tatevossian

The goal of the BEECD project was to prepare a basic parametric earthquake catalogue of Europe and a database of primary data, with special reference to long-term seismicity. This paper presents the main results of the project: a review of the current catalogues and the evaluation of their supporting datasets by means of a classification tool developed in the frame of the project; the investigation of more than 600 earthquakes; the start of the compilation of the European Intensity Database; the review of the procedures for the determination of the earthquake paramaters towards the compilation of a comprehensive European earthquake catalogue; the preparation of a website of the project.

EARTHQUAKE SCENARIO AND PROBABILISTIC GROUND SHAKING MAPS FOR THE PORTLAND, OREGON, METROPOLITAN AREA

I Wong, W. Silva, J. Bott, D. Wright, P. Thomas, N. Gregor, S. Li, M. Mabey, A. Sojourner, Y. Wang

We have developed the first quantitative earthquake scenario and probabilistic microzonation maps for ground shaking in the Portland, Oregon, metropolitan area. These GIS-based maps display colour-contoured ground motion values in terms of peak ground acceleration and horizontal spectral accelerations at 0.2- and 1.0-second periods. The maps depict ground shaking at the ground surface and thus incorporate the site-response effects of soils, unconsolidated sediments, and shallow rock. The scenario maps are for a moment magnitude (MW) 9.0 earthquake along the megathrust of the Cascadia subduction zone and a hypothetical MW 6.8 event on the Portland Hills fault. The probabilistic maps are for two return periods of building code relevance, 500 and 2,500 years. It is our hope that these maps will be used by governmental agencies, the engineering, urban planning, emergency preparedness and response communities, and the general public as part of an overall effort to reduce earthquake hazards in the Portland metropolitan area.

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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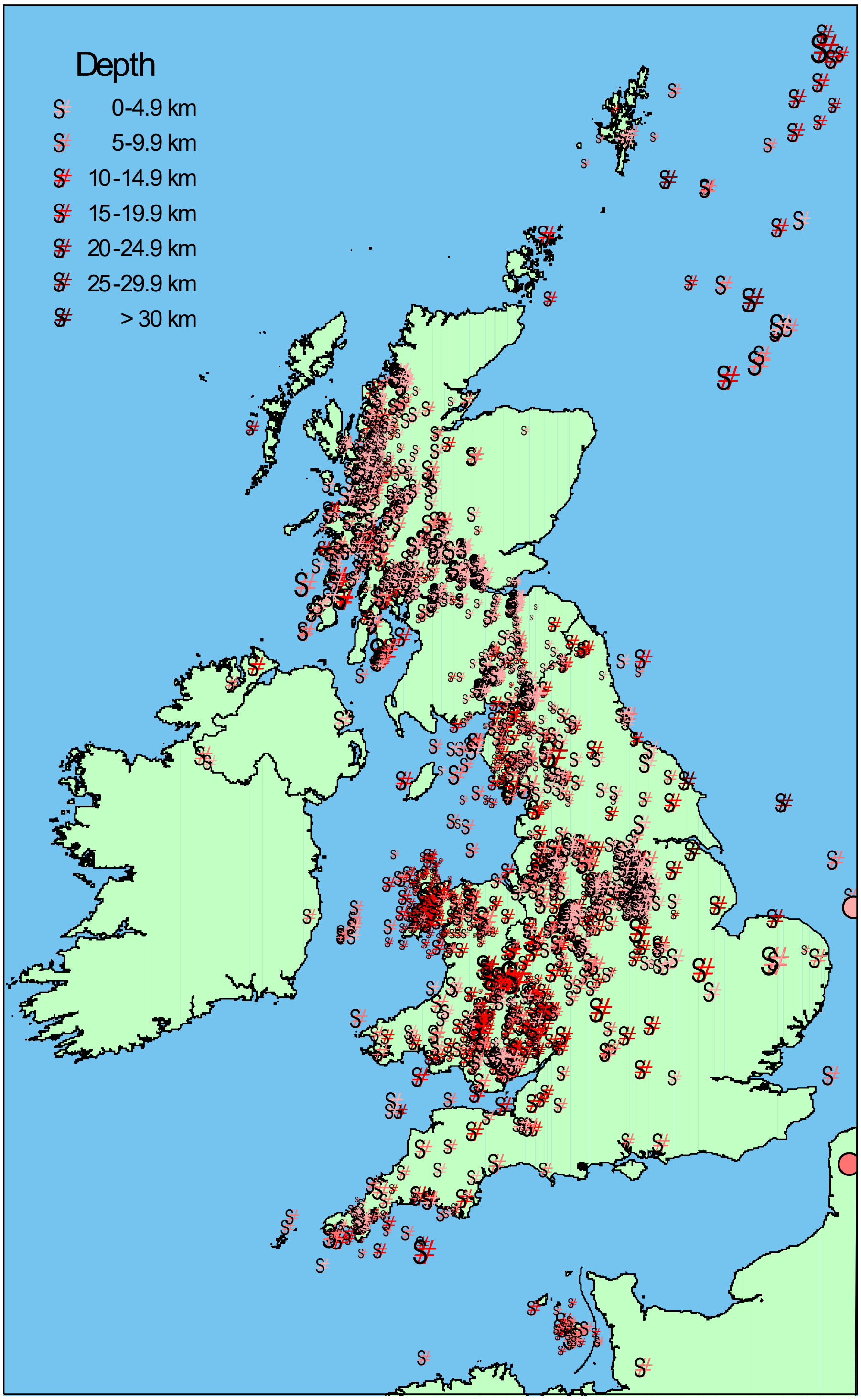

Depth distribution of UK Seismicity 1970-April 2000